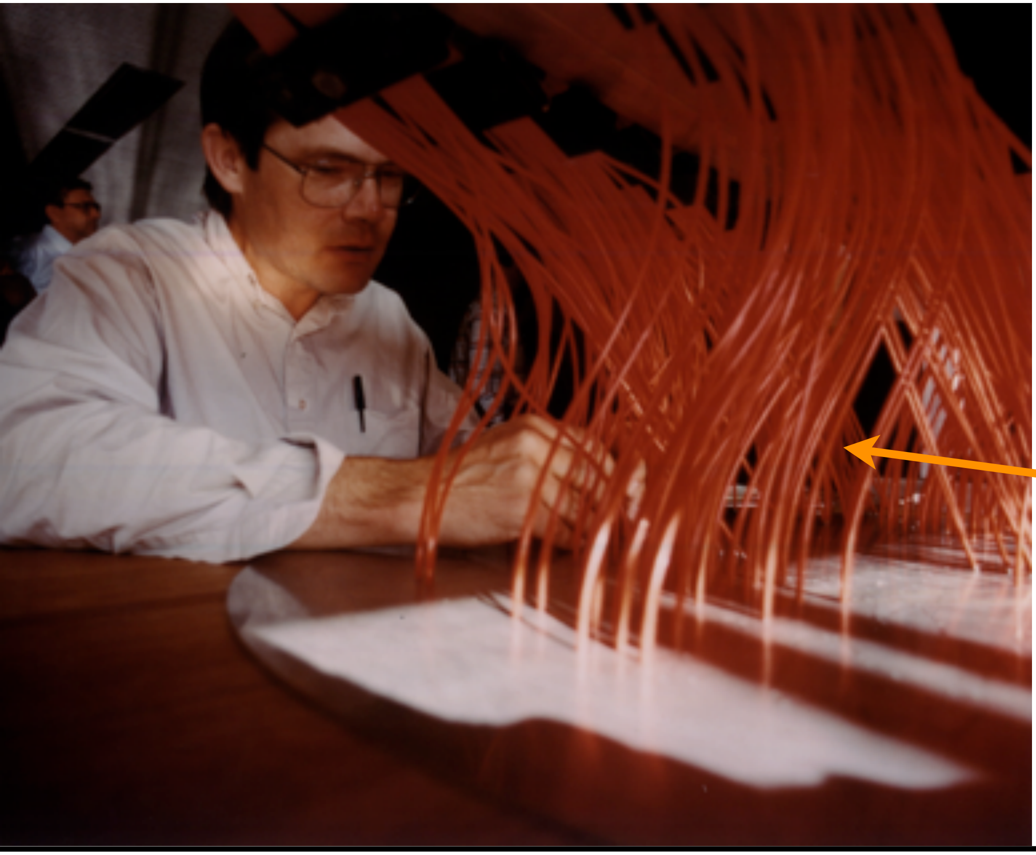
BigBOSS

David Schlegel
on behalf of the BigBOSS collaboration

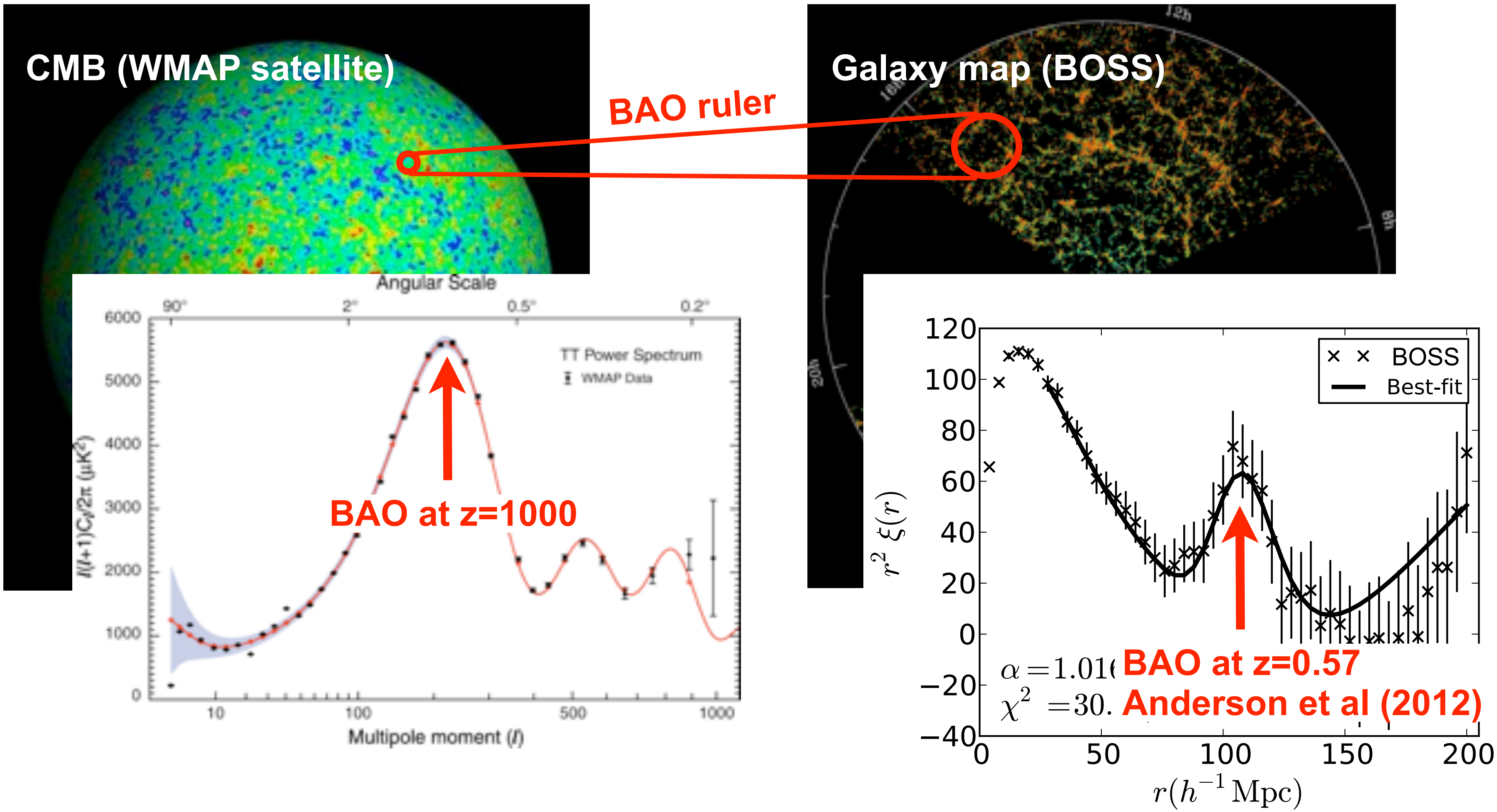
BOSS was the 1st Stage III D.E.

BOSS is trailblazer for BigBOSS
Plug plates do not scale to more than 0.5 million objects/year



BOSS is the 1st Stage III D.E.

Dec 2007: Spectrograph proposal to DOE
Dec 2009: Survey start
March 2012: First results from BOSS supersede all previous BAO at z=0.57
Nov 2012: First results from BOSS (or anyone!!) at z > 2



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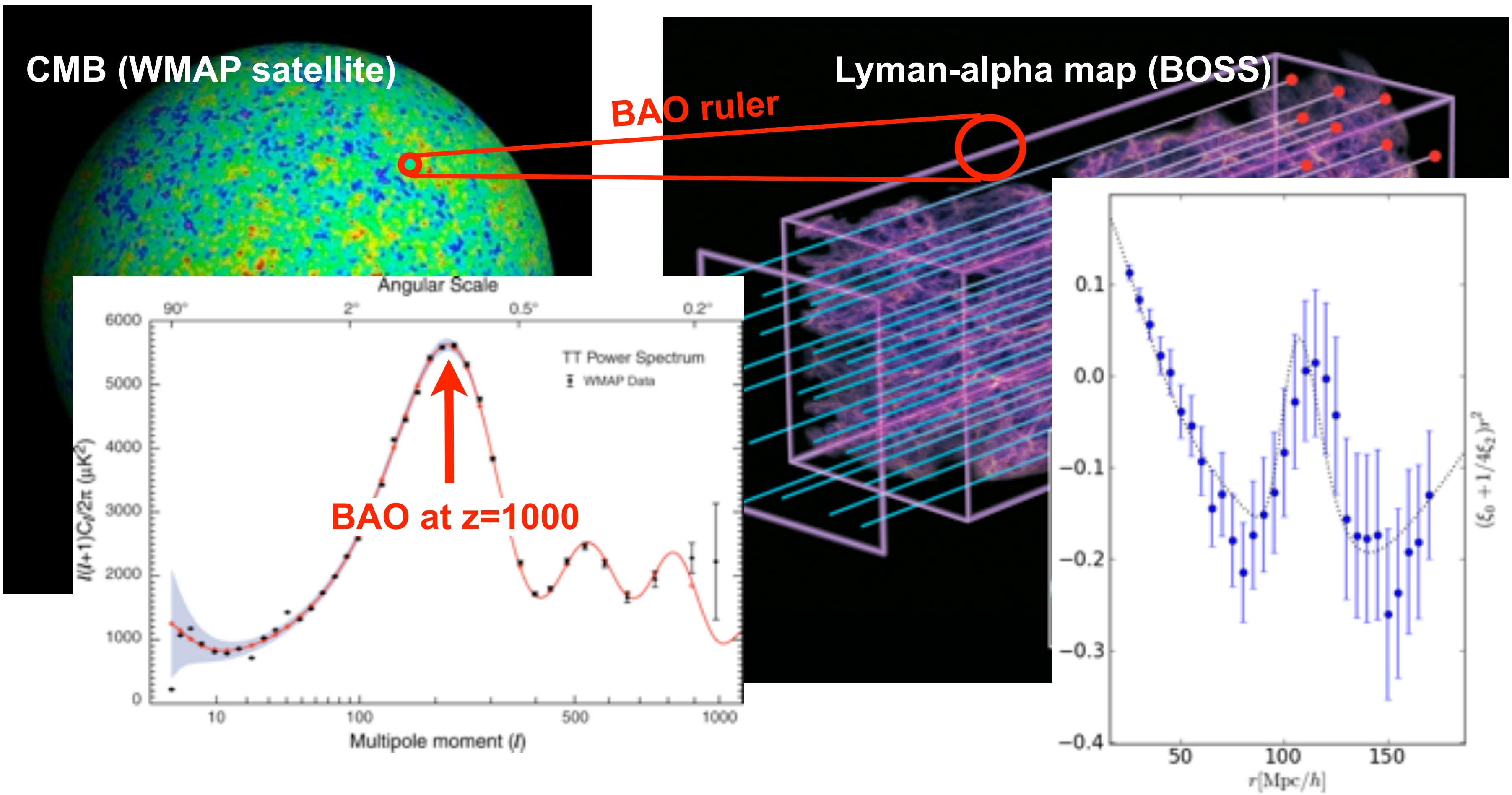


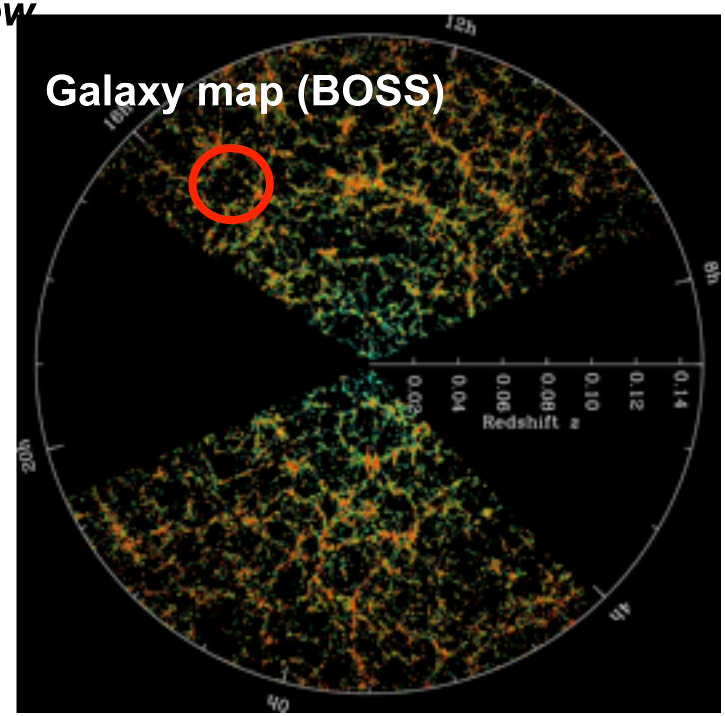
Why was BOSS so easy?

Target photometry uniform from SDSS

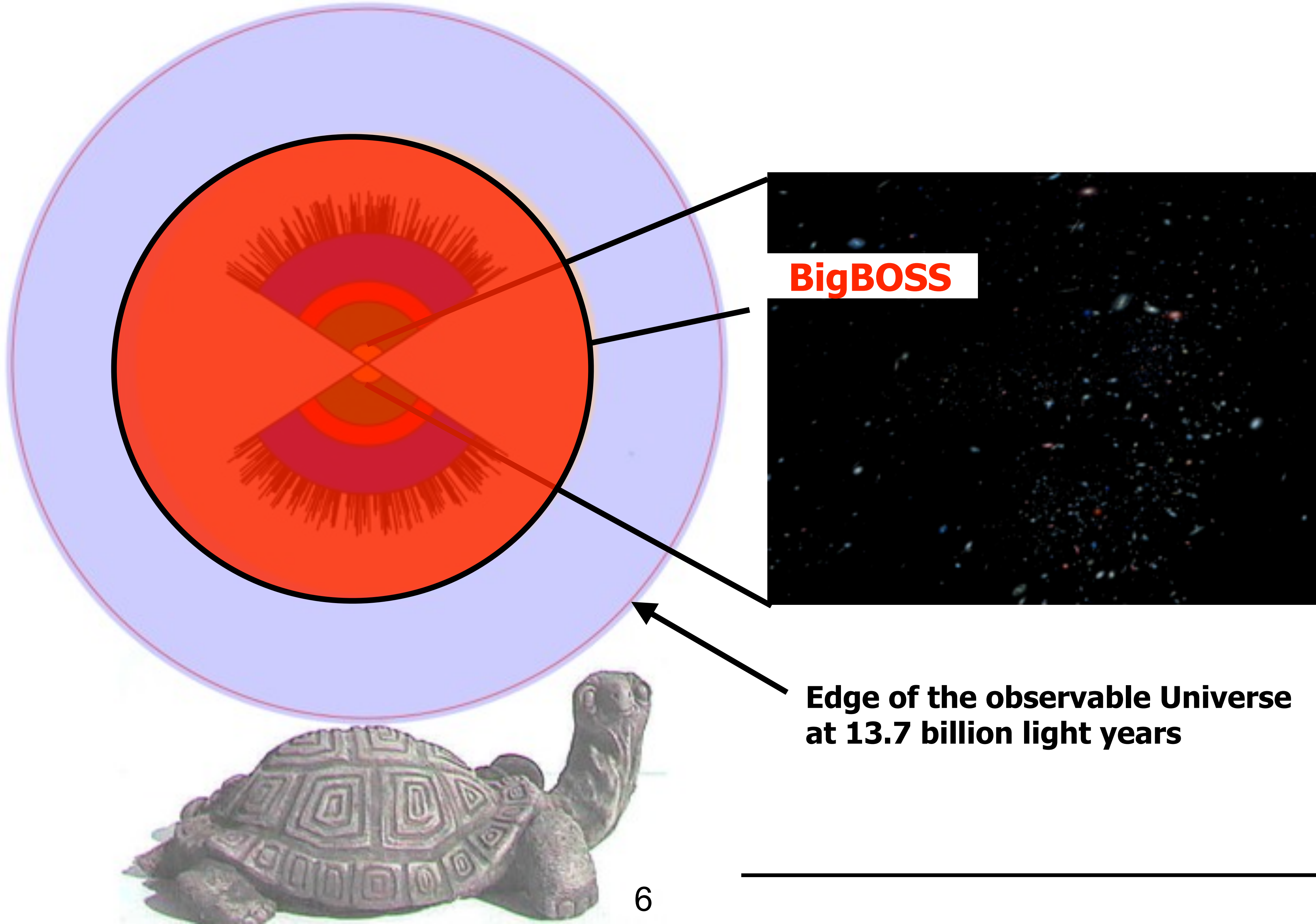
Target photometry systematics ~1%
...although objects are faint, and S/N ~ few

Spectroscopy observed to uniform depth
+ full wavelength coverage

Spectroscopy is 98% complete
No other large survey even comes close



BOSS will only map ~0.5% of modes in observable Universe



A map of only 0.5% (ie., BOSS) ?

BigBOSS designed as 1st Stage IV D.E.

Dark Energy Task Force defined progressive capabilities

For BAO:

- **Stage I: knowledge ca. 2006**
  - BAO detection by SDSS-I
- **Stage II: running experiments**
  - SDSS-I + SDSS-II, WiggleZ
- **Stage III: near-term experiments**
  - 3X better than Stage II: SDSS-III/BOSS, HETDEX
- **Stage IV**
  - 10X better than Stage II: BigBOSS

BigBOSS Collaboration formed 2009

US Groups:

Brookhaven National Laboratory
Carnegie Mellon University
Fermi National Accelerator Laboratory
Johns Hopkins University
Lawrence Berkeley National Laboratory
National Optical Astronomy Observatory
New York University
The Ohio State University
SLAC National Accelerator Laboratory
University of California, Berkeley
University of California, Santa Cruz/Lick Observatory
University of Kansas
University of Michigan
University of Pittsburgh
University of Utah
Yale University

Non-U.S. Groups:

Ewha Womans University, Korea
French Participation Group
APC, IAP- Paris; CPP, CPT, LAP Marseille; CEA, IRFU – Saclay
Spanish Participation Group
IAA, Granada; IAC, Tenerife; ICC, Barcelona; IFT, Madrid; U. Valencia
Shanghai Astronomical Observatory
UK Participation Group
Durham, Edinburgh, UC London, Portsmouth
University of Science and Technology of China

BigBOSS timeline

Apr 2009 White paper
Nov 2009 DOE Particle Astrophysics Science Advisory Group (PASAG)

"BigBOSS is in the early planning stages, but presents a legitimate possibility of achieving a significant fraction of the BAO science goals for JDEM at <$100M cost. **Substantial immediate support is recommended for BigBOSS R&D so that ground BAO possibilities are known for timely planning of a coherent ground-space dark energy effort.**"

Nov 2009 NOAO call *"Large Science Programs Providing New Observing Capabilities for the Mayall 4m Telescope on Kitt Peak"*

Aug 2010 Astro2010 Decadal Survey

BigBOSS highly recommended as 1 of 4 "Projects Thought Compelling for the Mid-Scale Innovations Program" in the cost range $US 40-100 million.

Oct 2010 NOAO telescope time

495 night survey program awarded.

BigBOSS timeline

December 2011 - Department of Energy (DOE) review

"In summary, the panel believed that the R&D plan will lead to a mature technical design within 18 months. The panel found that the management team is clearly ready to move ahead with the project as soon as the external hurdles are cleared, including the telescope availability, and roles and responsibilities of the lead laboratories and funding agencies. The management should work with the stakeholders and agencies to bring BigBOSS to a condition where CD-0 approval can be requested expeditiously. Due to the maturity of the collaboration and design, critical decision 1 (CD-1) approval could quickly follow."

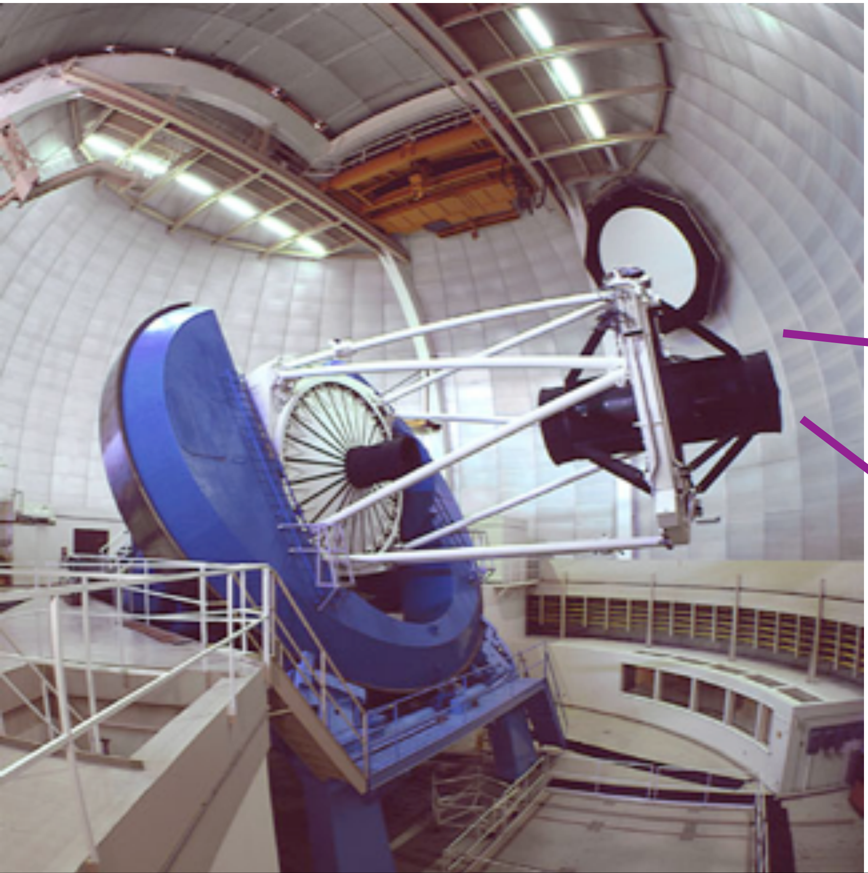
August 2012 - National Science Foundation "Portfolio Review"

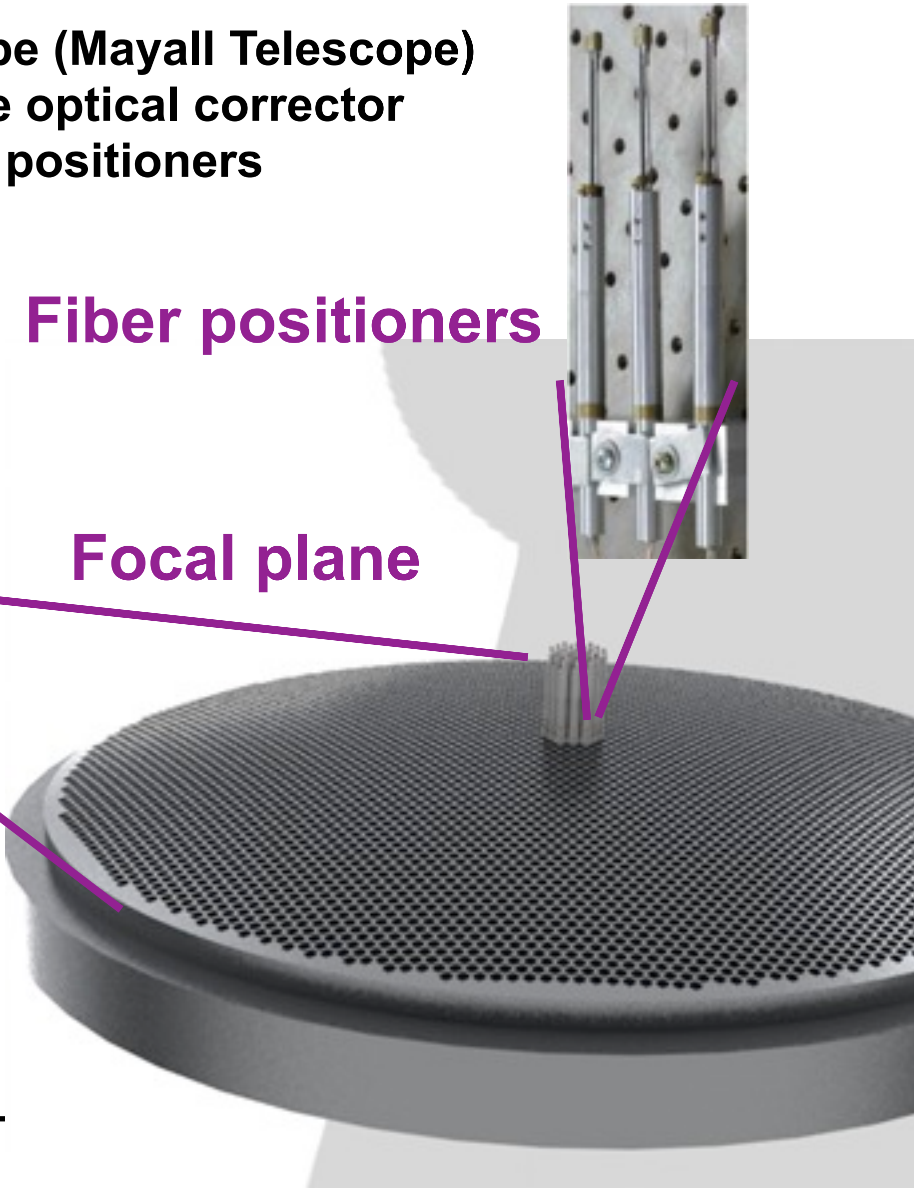
- ***Endorses capability of BigBOSS on a 4-m telescope, ranked just after LSST in importance to Cosmology and Fundamental Physics***
- ***Recommends "divestment" of NSF from the Mayall telescope by 2017***
- ***BigBOSS could operate Mayall telescope full-time starting in 2017 for either a faster survey, or more ambitious 1500-night project in 5 years***

BigBOSS: Stage IV BAO

BigBOSS designed as Stage IV BAO

- **Redshift depth from 4-m telescope (Mayall Telescope)**
- **Volume of universe with 3-degree optical corrector**
- **Numbers from 5000 robotic fiber positioners**





BigBOSS: Stage IV BAO

Instrument

3 deg diameter FOV prime focus corrector
5000 fiber positioner, 1 min. reconfiguration
10 x 3-arm spectrographs, 3600-9800 Ang

Analysis pipeline

Key Project

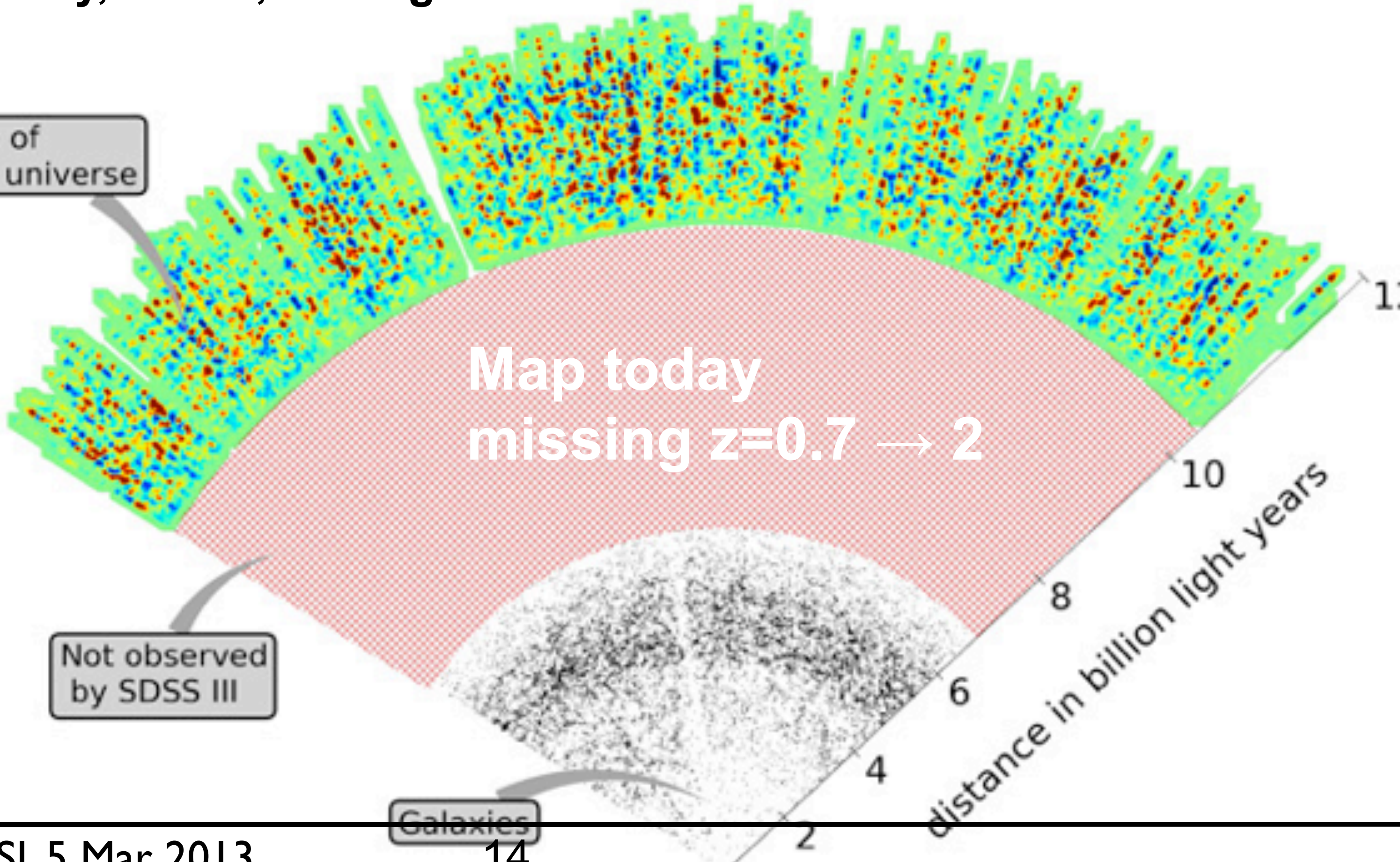
495 nights at Mayall 3.8-m
14,000 deg^2 survey
50,000,000 spectra of 24 million targets

4 million	1. Luminous Red Galaxies (LRGs)	$z = 0.5 \rightarrow 1$	2 exposures
18 million	2. Emission Line Galaxies (ELGs)	$z = 0.5 \rightarrow 1.6$	1 exposure
2.5 million	3. Tracer QSOs	$z = 0.5 \rightarrow 3.5$	1 exposure
1 million	4. Lyman-alpha QSOs	$z > 2.1$	5 exposures

BigBOSS: Stage IV BAO

BigBOSS designed as Stage IV BAO

Requires:
- **spectroscopic redshifts**
- **>20 million objects spanning z=0→2**
- **~1/3 of full sky, or ~14,000 deg^2**



BigBOSS: Stage IV BAO

BigBOSS designed as Stage IV BAO

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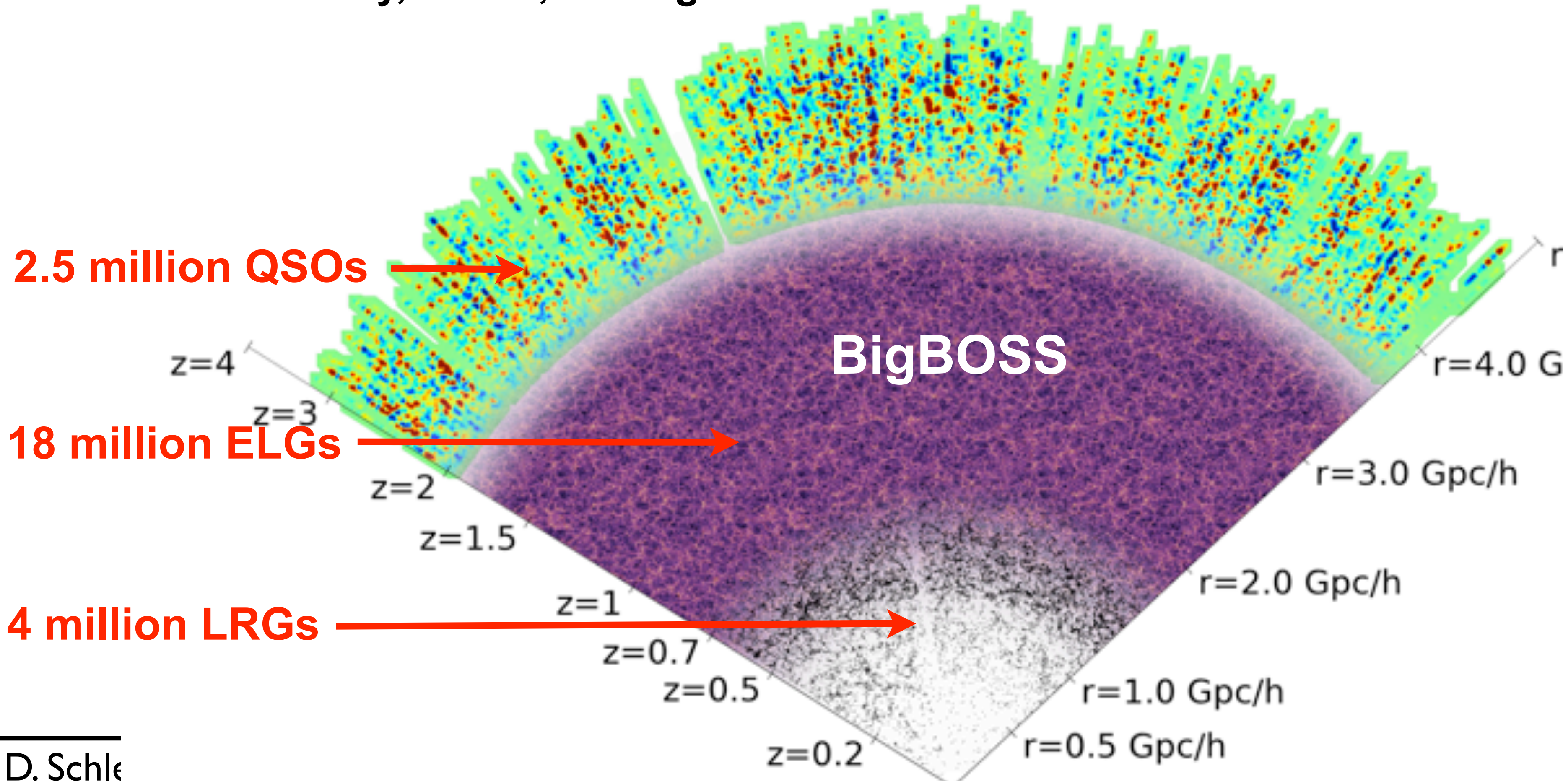


D. Schle

BigBOSS targets

Four target categories:

1. Luminous Red Galaxies (LRGs) — **4 million LRGs**

- Selected to z<1
- Efficient BAO tracers due to large bias

2. Emission Line Galaxies (ELGs) — **18 million ELGs**

— Selected 0.5<z<1.6 when the Universe was forming stars

— Redshifts from [O II] emission lines

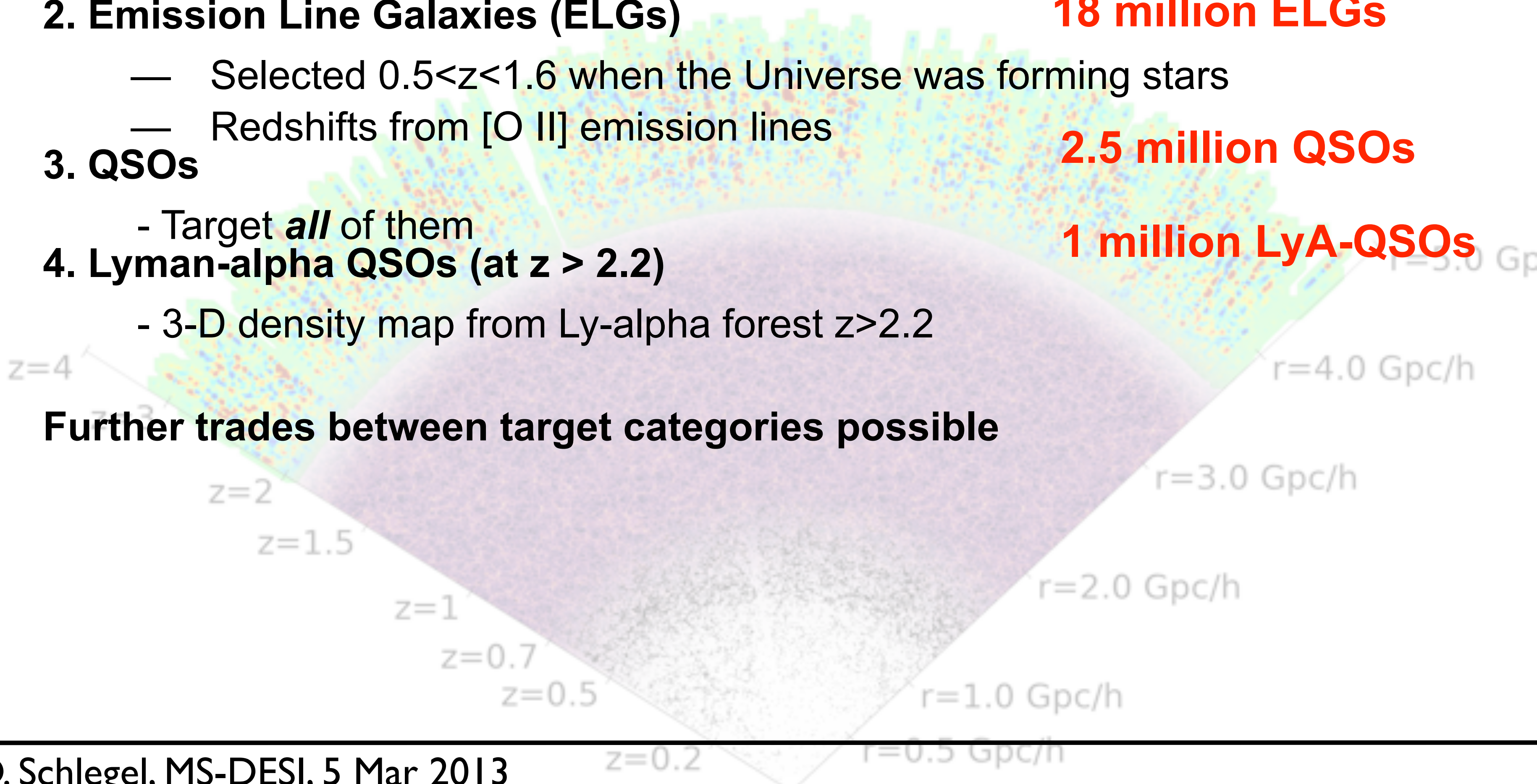
3. QSOs — **2.5 million QSOs**

- Target ***all*** of them

4. Lyman-alpha QSOs (at z > 2.2) — **1 million LyA-QSOs**

- 3-D density map from Ly-alpha forest z>2.2

Further trades between target categories possible



1. Luminous Red Galaxies (LRGs)

LRGs have been the workhorse of BAO surveys (SDSS, BOSS)
All LRG spectra look nearly identical to z~1

Entire spectrum used for redshift,
dominant features are "4000 Angstrom break" and "Ca H+K lines" to z=1.2

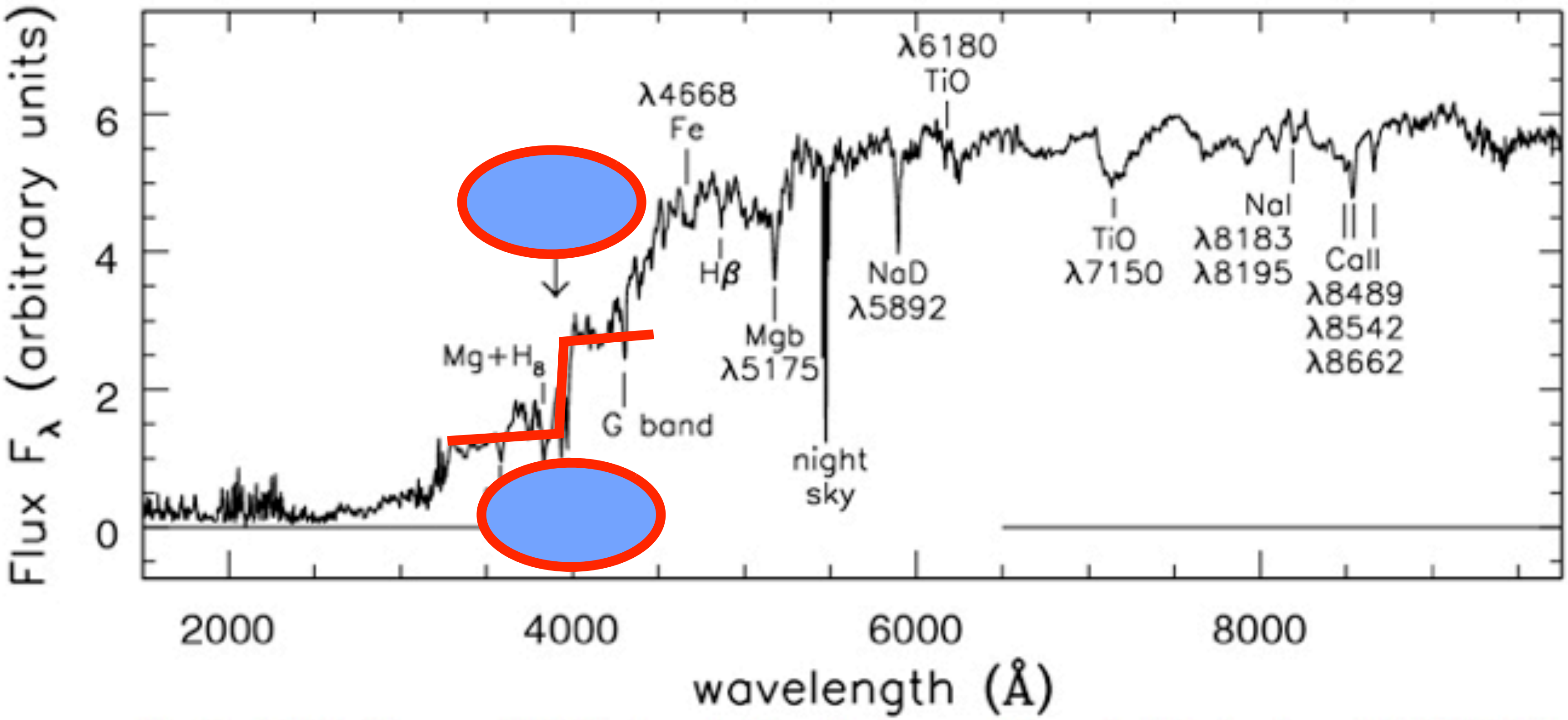


Fig 6.17 (A. Kinney) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

1. Luminous Red Galaxies (LRGs)

LRG tracers at 0.5 < z < 1

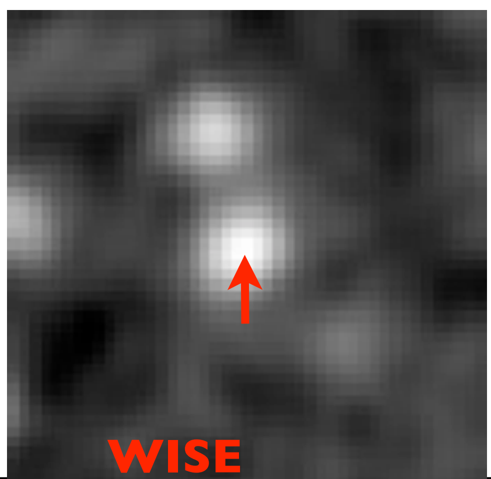
The most massive galaxies in the Universe
Excellent tracers of dark matter halos
Well-studied in N-body simulations

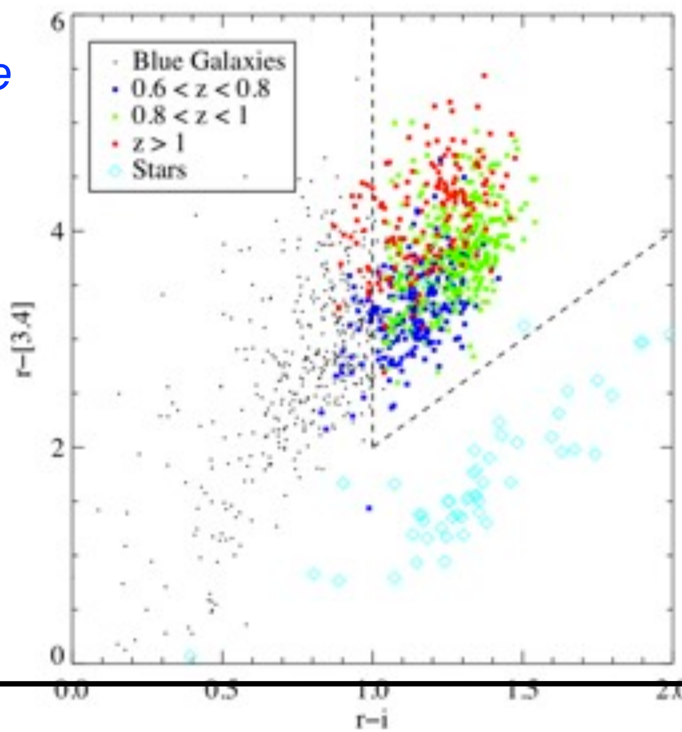
Test data:

1.5 million LRGs from SDSS + SDSS-II + BOSS to z=0.7
+20,000 LRGs from BOSS ancillary programs in 2012-2013

BigBOSS targets:

4 million LRGs to z=1
Selected at 3.4 micron from WISE satellite
+ SDSS/ZTF imaging (2-band only)

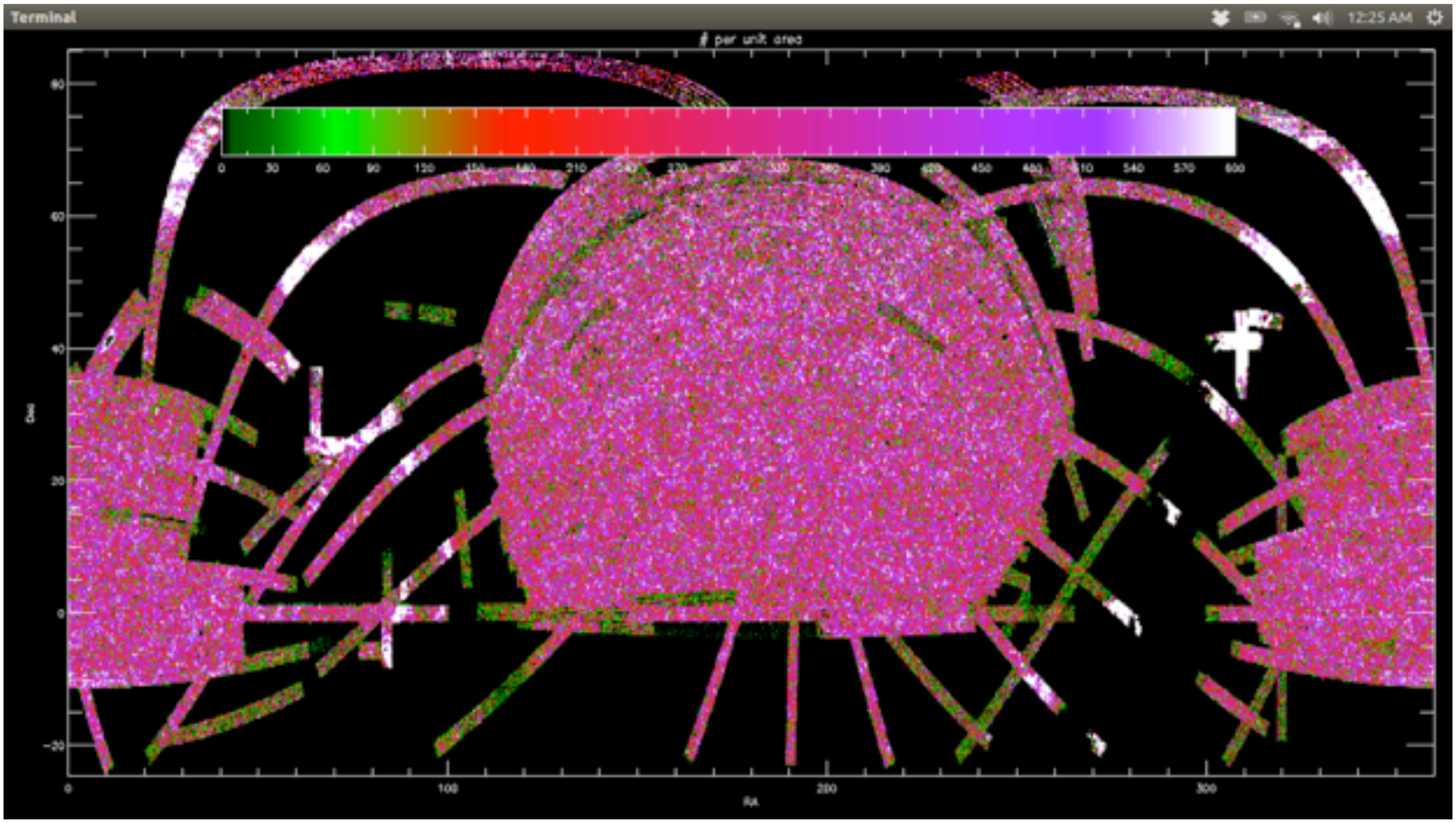




1. Luminous Red Galaxies (LRGs)

SDSS + WISE

1.4 million LRGs selected to i=22 in SDSS (preliminary!)



Jeff Newman, Tim Licquia

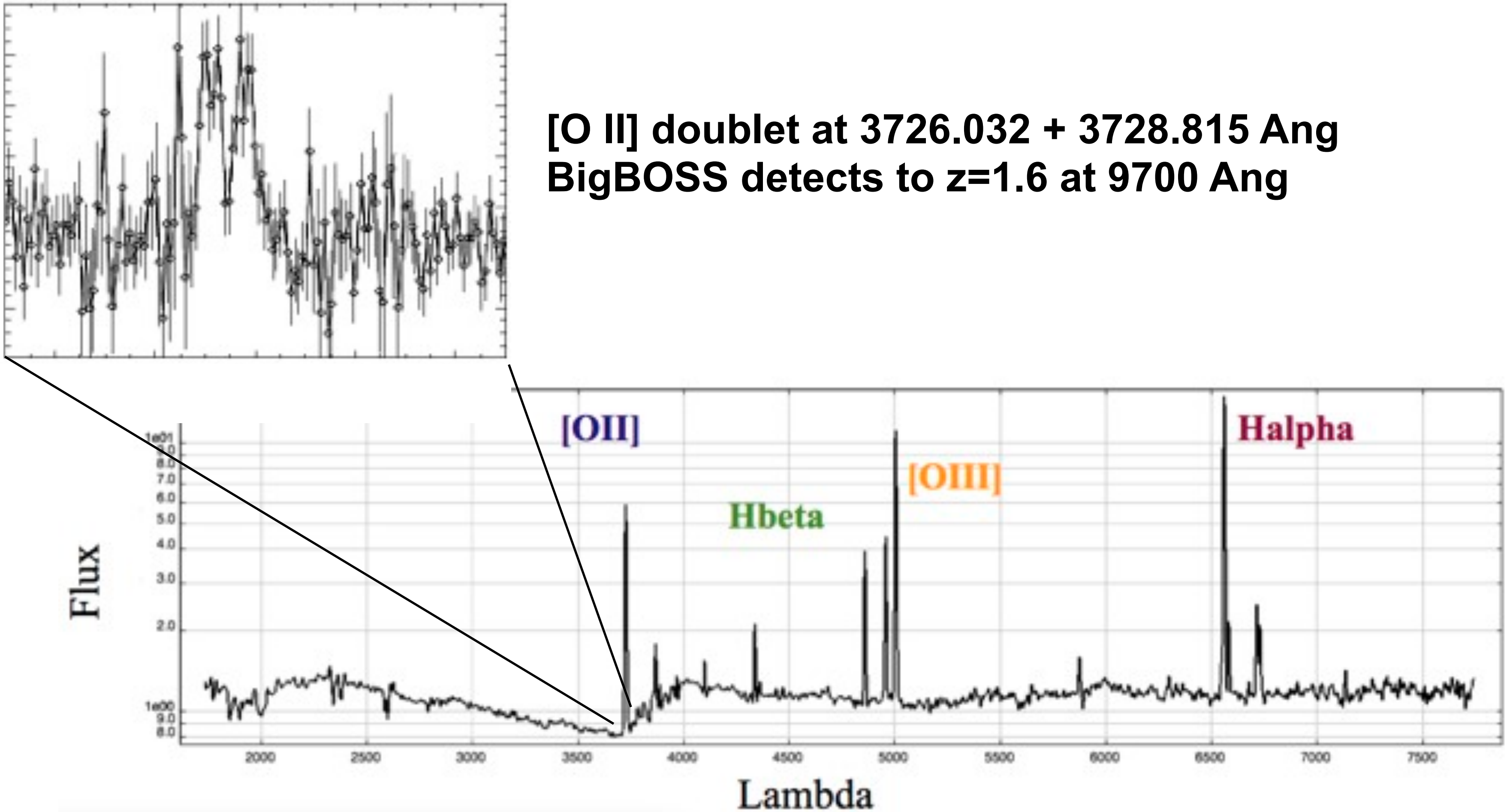
2. Emission Line Galaxies (ELGs)

ELGs unique signature of [O II] doublet, detectable from z=0 to z=1.7

Well-studied as the ~5% brightest galaxies in the DEEP2 survey

ELGs drive BigBOSS wavelength coverage, throughput, & resolution

[O II] doublet at 3726.032 + 3728.815 Ang
BigBOSS detects to z=1.6 at 9700 Ang



2. Emission Line Galaxies (ELGs)

ELGs tracers at 0.5 < z < 1.6

Epoch of star formation peaks in these galaxies at z~1

Easy to select from optical colors

Test data:

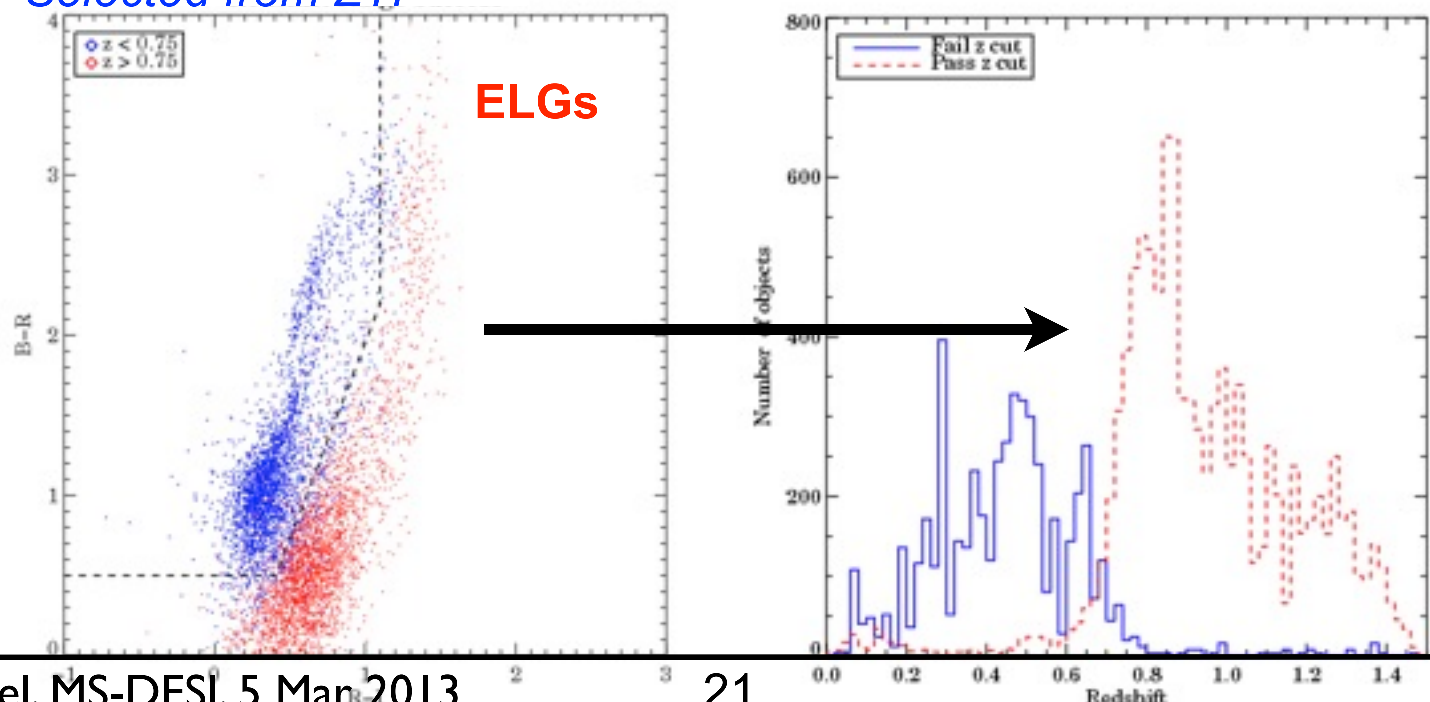
40,000 ELGs from DEEP2, VVDS over 4 deg2 total

+40,000 ELGs from BOSS ancillary programs in 2012-2013 to z=1.6

BigBOSS targets:

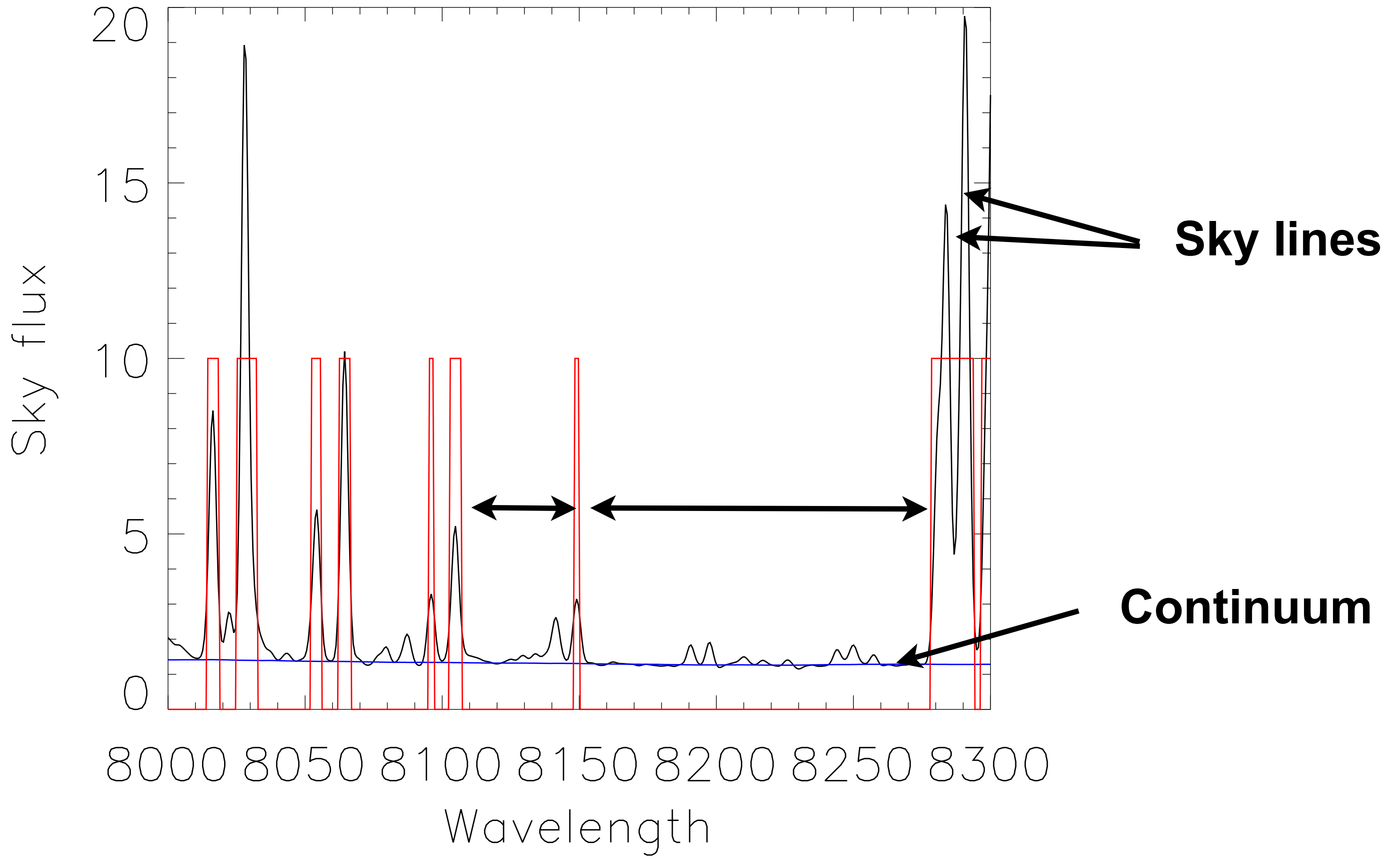
18 million ELGs in BigBOSS survey

Selected from ZTF



2. Emission Line Galaxies (ELGs)

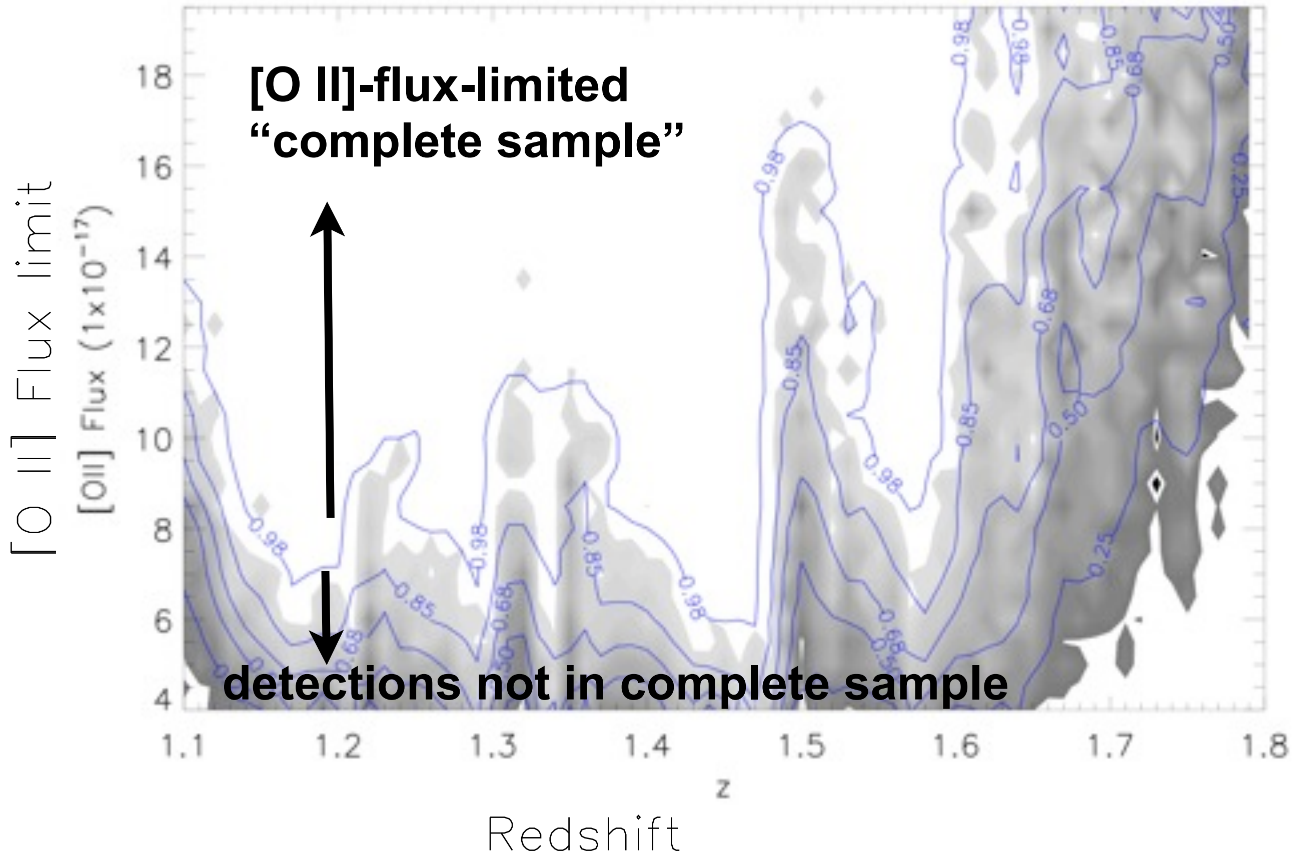
ELG complete sample requires R > 5000 for free spectral range



Higher resolution → Increased free spectral range
~80% for R=4000

2. Emission Line Galaxies (ELGs)

ELG complete sample requires R > 4000 for high-confidence redshifts

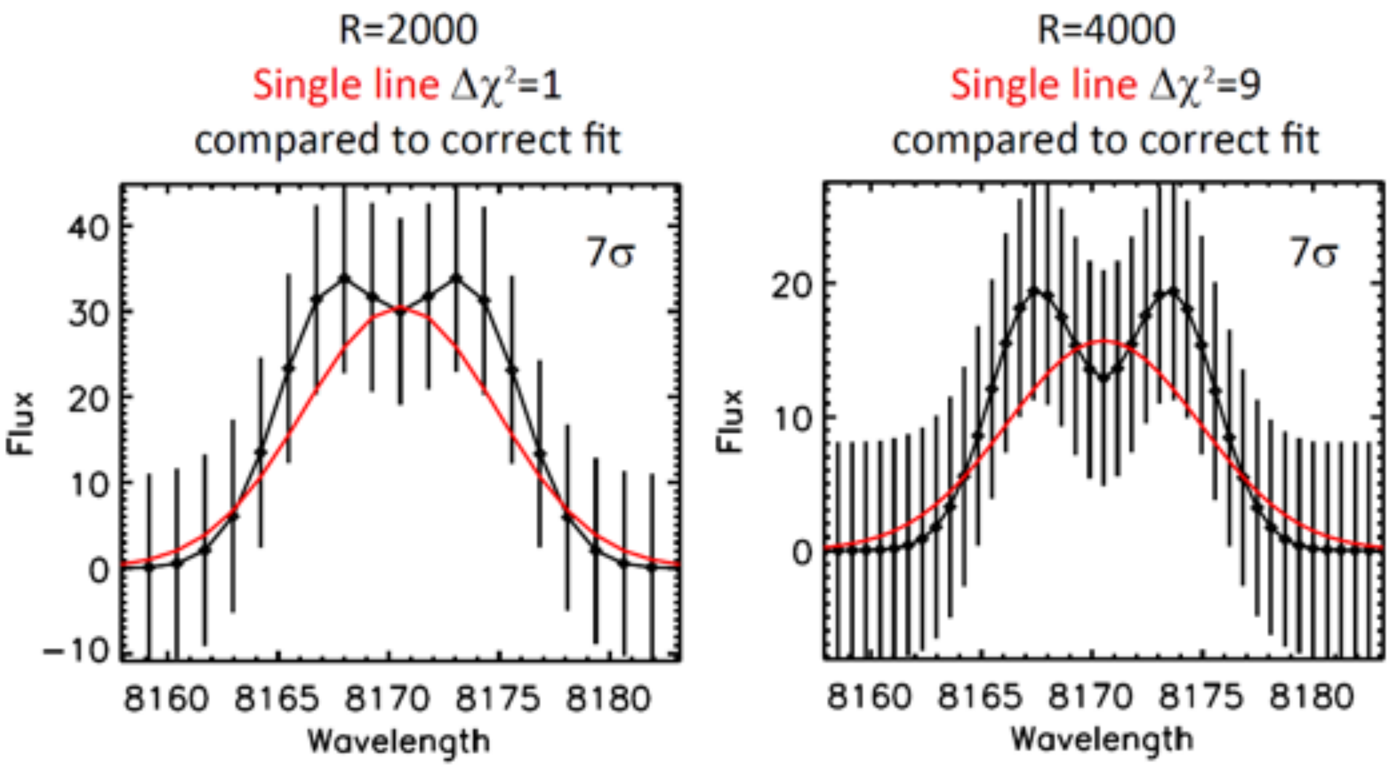


Nick Mostek

2. Emission Line Galaxies (ELGs)

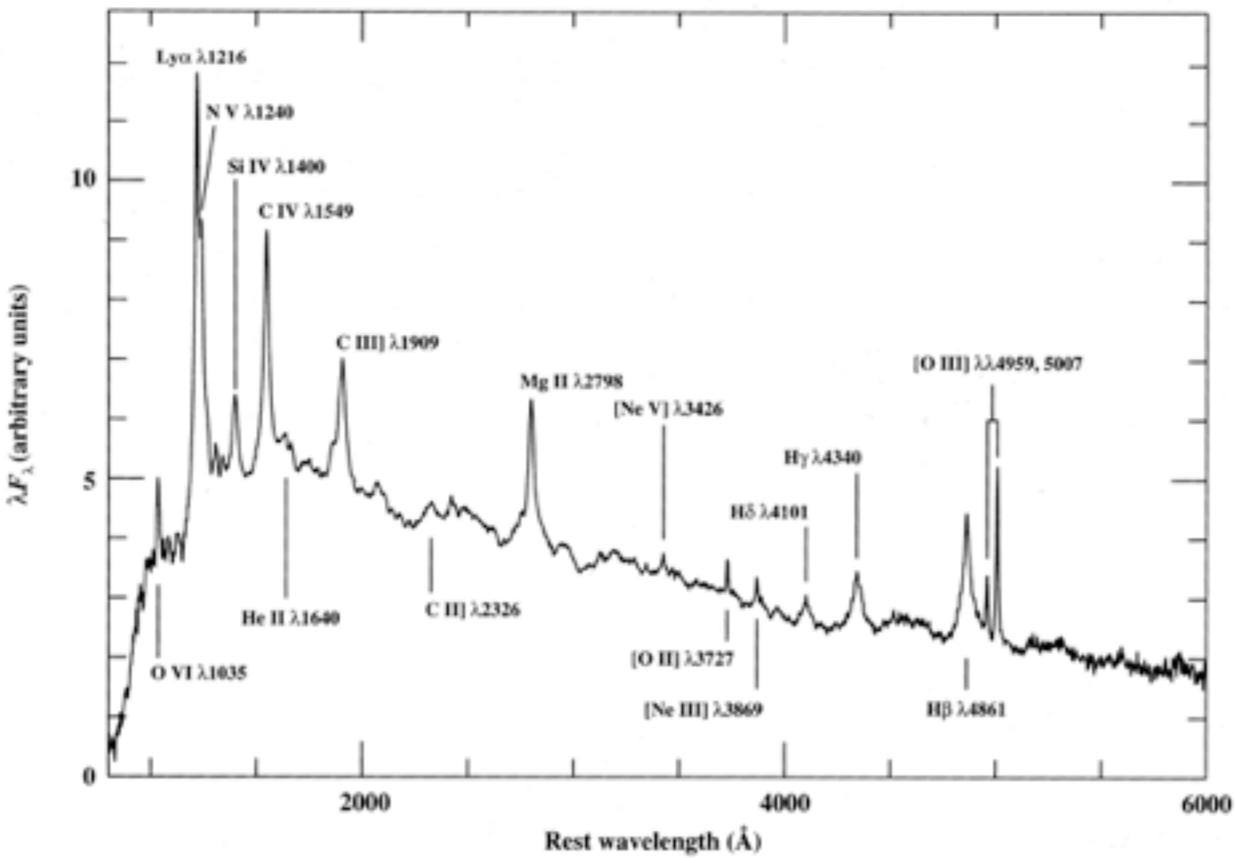
ELG complete sample requires R > 5000 for high-confidence redshifts

— **At R=2000, [OII] doublet at 7-sigma is degenerate with a single-line identification of anything**



3. QSOs as tracers

QSO spectra are obvious even at very faint S/N
BOSS survey easily identifies to g=22, BigBOSS extends to g=23.5

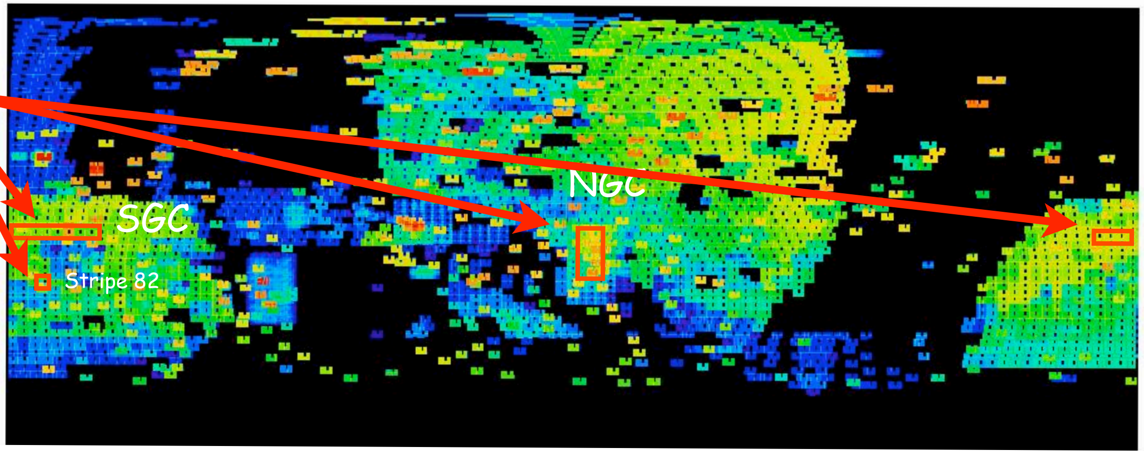


3. QSOs as tracers

QSO tracers at 0.5 < z < 3.5
The brightest objects at z > 2
+ QSO Lyman-alpha forest at 2.2 < z < 3.5

Test data:
BOSS spectra for 160,000 to g=22
+15,000 QSOs from BOSS +MMT ancillary programs to g=23.5
BigBOSS targets:
2.5 million QSOs from ZTF
Every QSO to r < 23.5
Simplify target selection: select QSOs at all redshifts from variability
Being studied now: select using WISE photometry (complete)

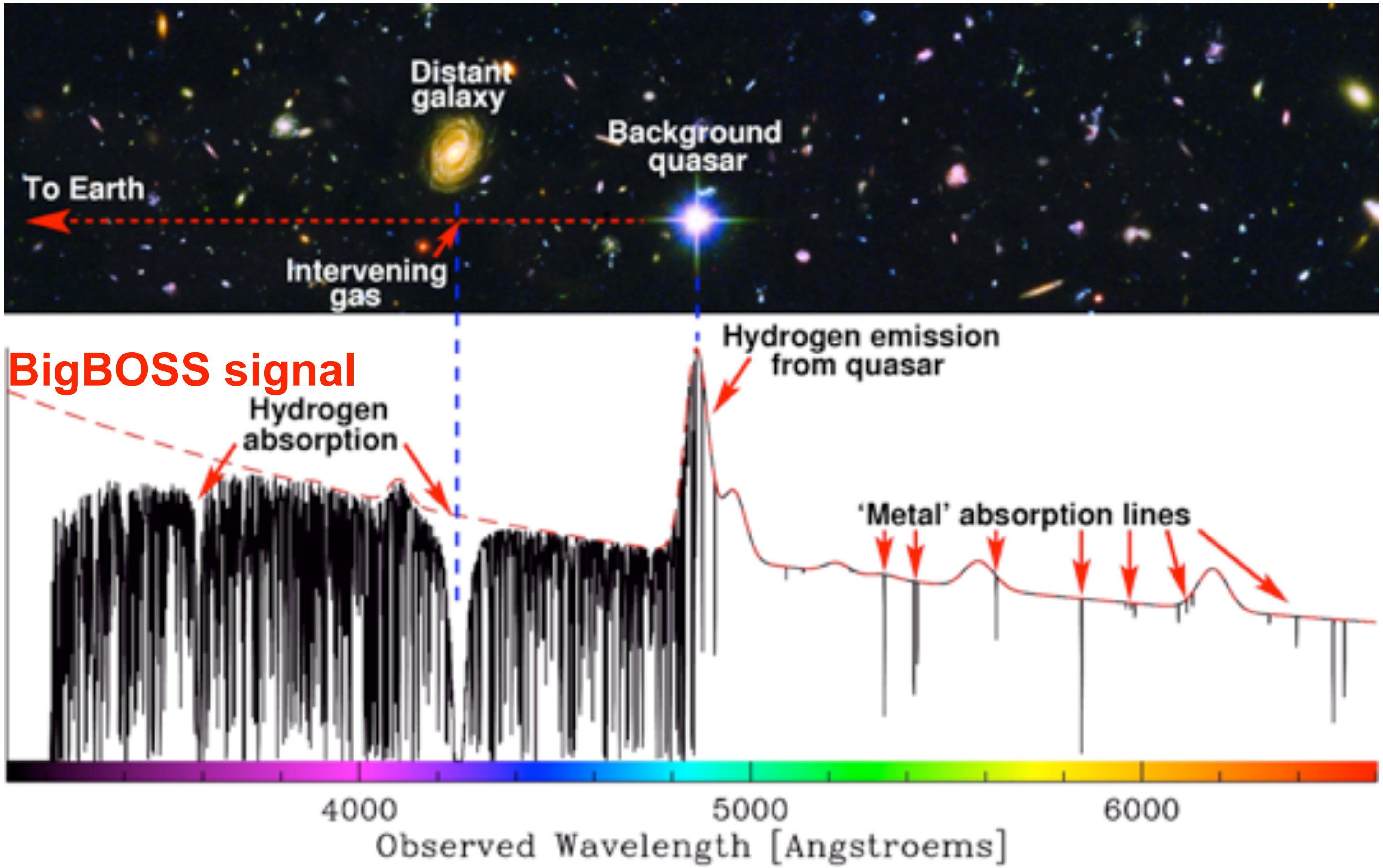
PTF test fields



4. Lyman-alpha forest from QSOs

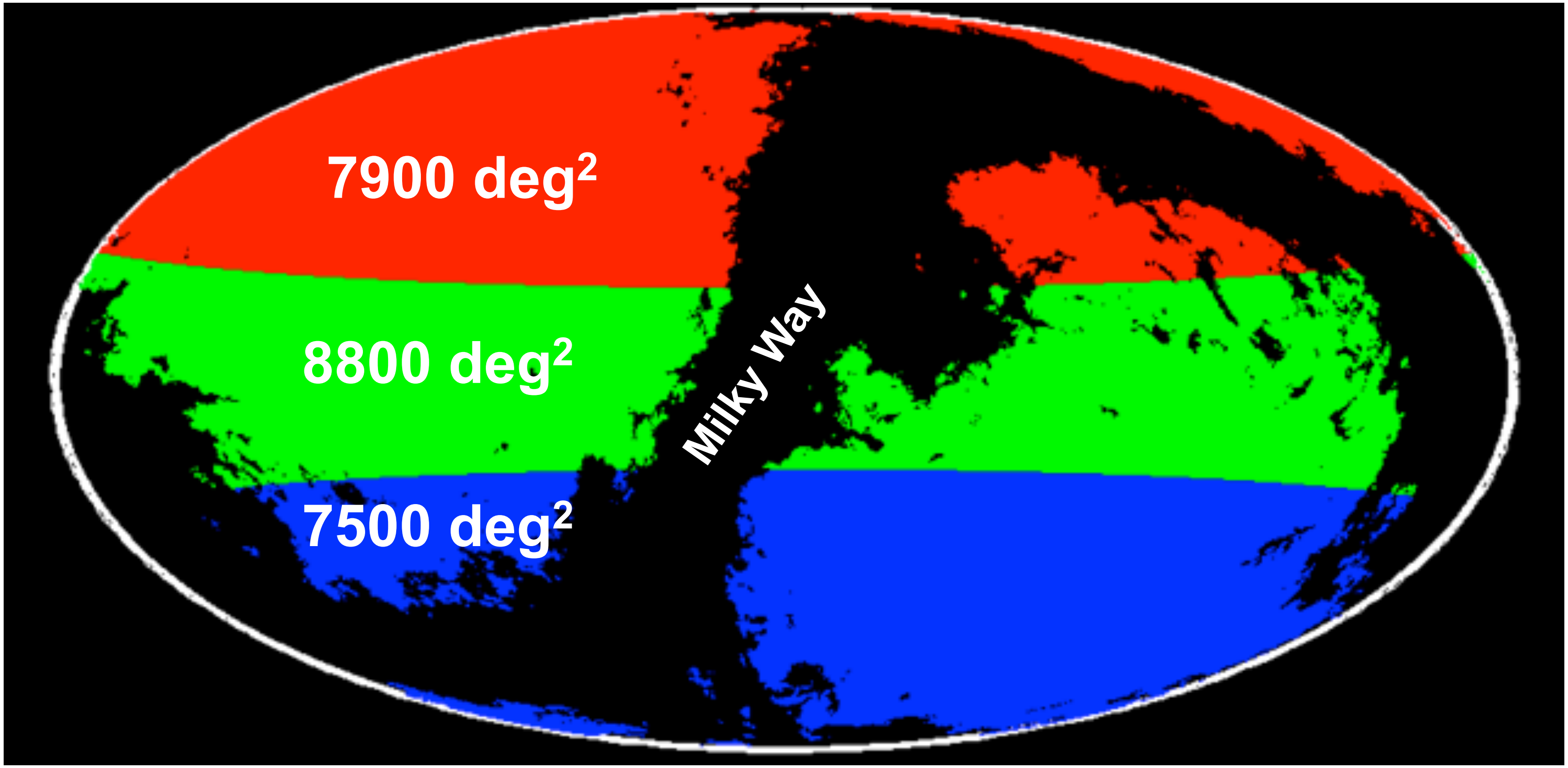
QSOs at z < 2.2 will be observed once → "tracer QSOs"
QSOs at z > 2.2 will be observed 5X for high S/N for "Lyman-alpha forest"

Map of hydrogen gas along line-of-sight skewers
BOSS has demonstrated their use as 3-D maps for BAO



BigBOSS target sources

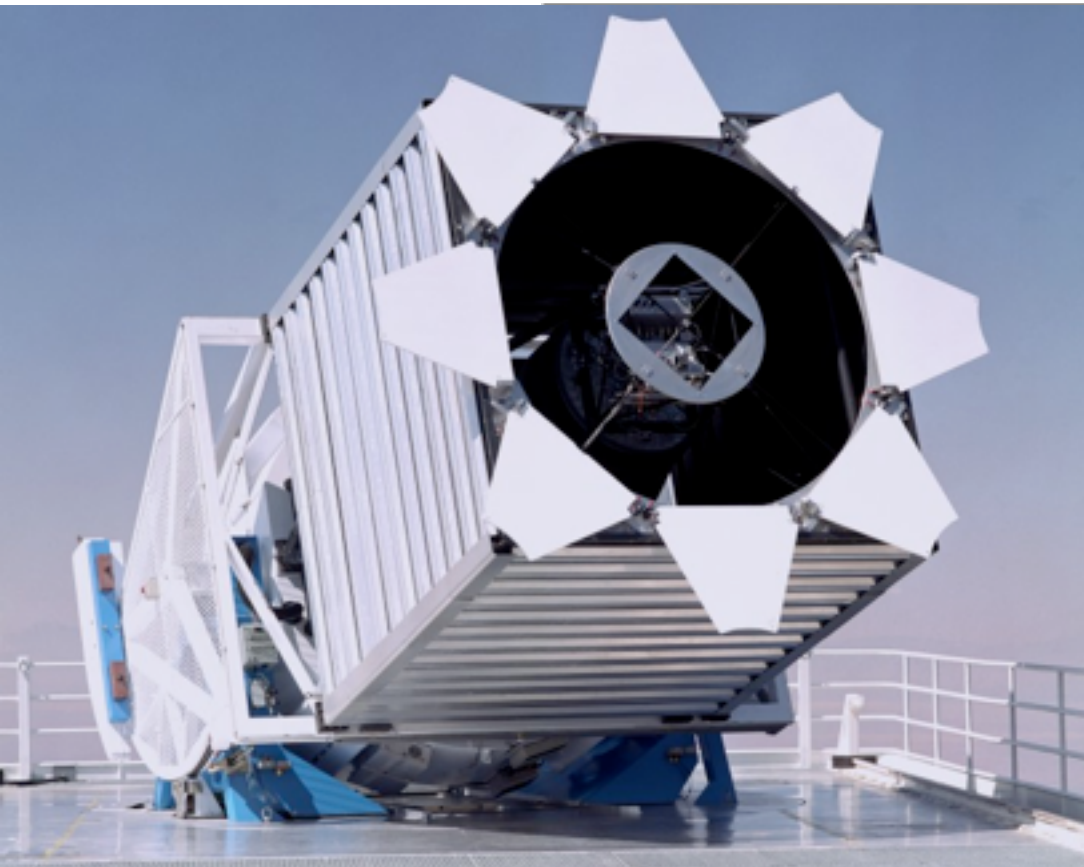
SDSS -> PTF -> ZTF (optical)
WISE (infrared for LRGs, QSOs)
GAIA (astrometry)

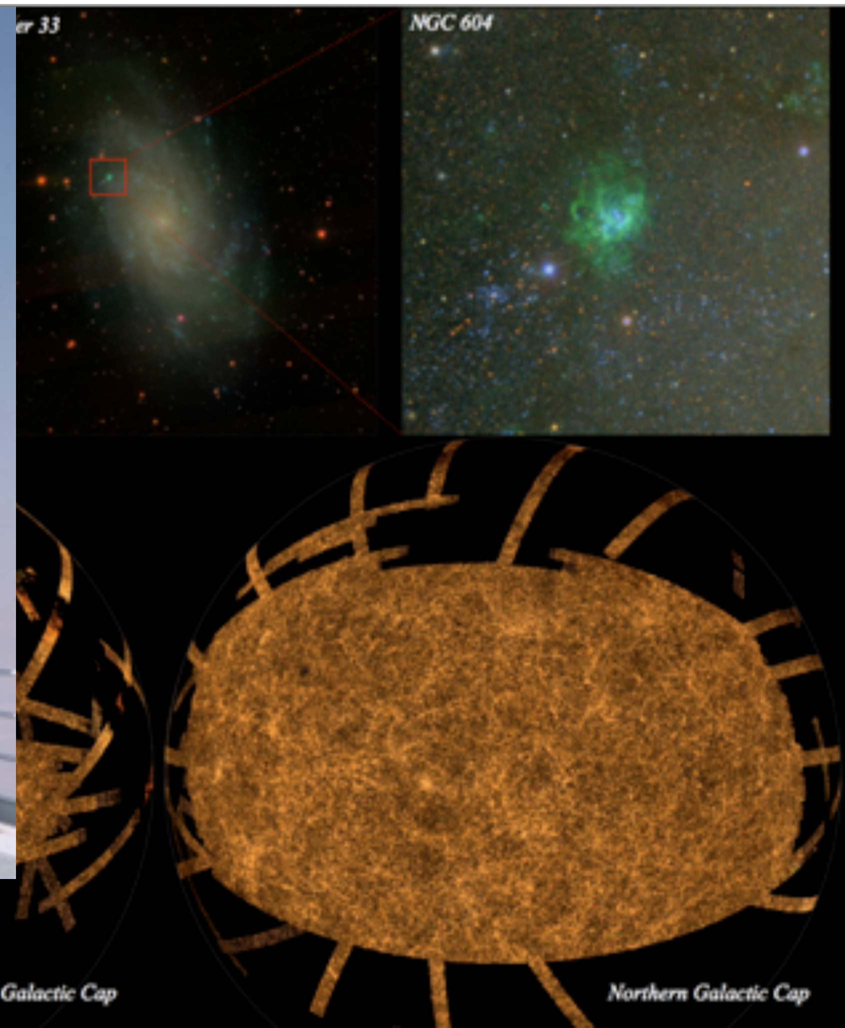


SDSS

Complete to 11,000 deg^2 extragalactic
Best-calibrated wide-area survey
- **~1% systematics for BOSS targets; Schlafly & Finkbeiner (2012) <0.5%**

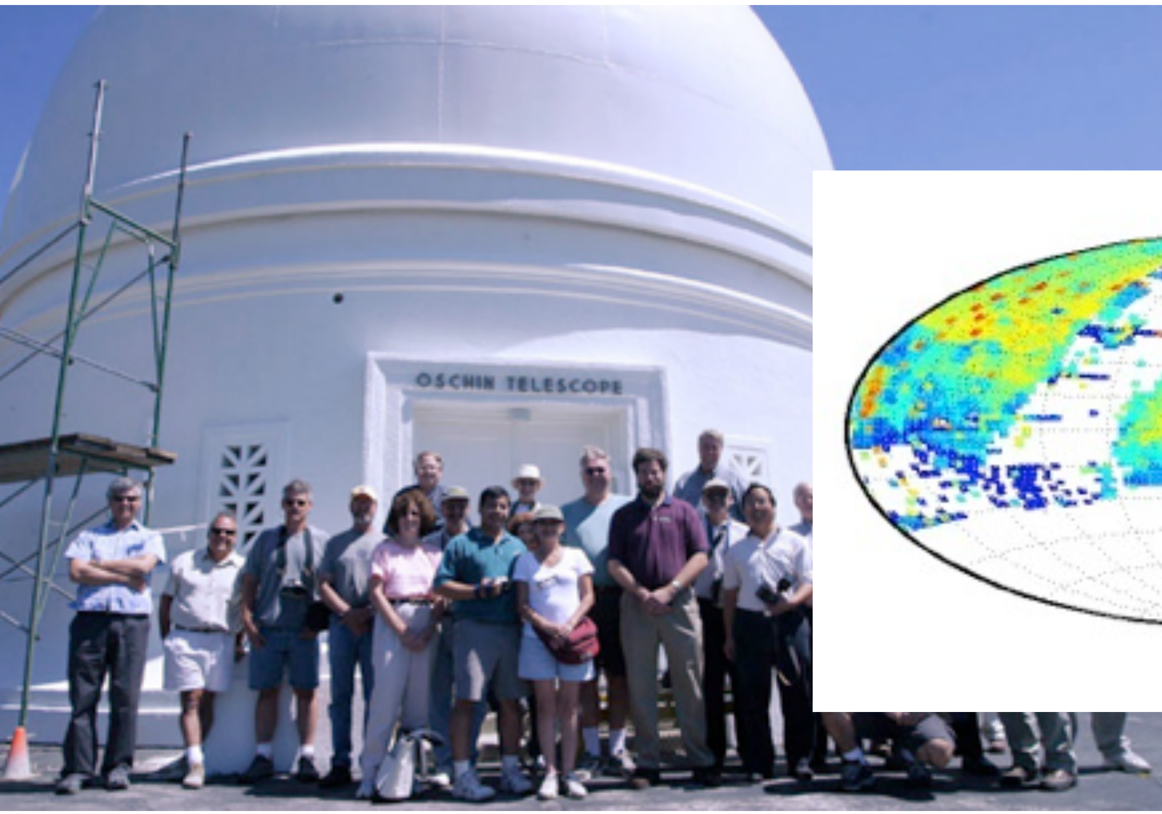
Deep enough for the brightest ~7 million BigBOSS targets

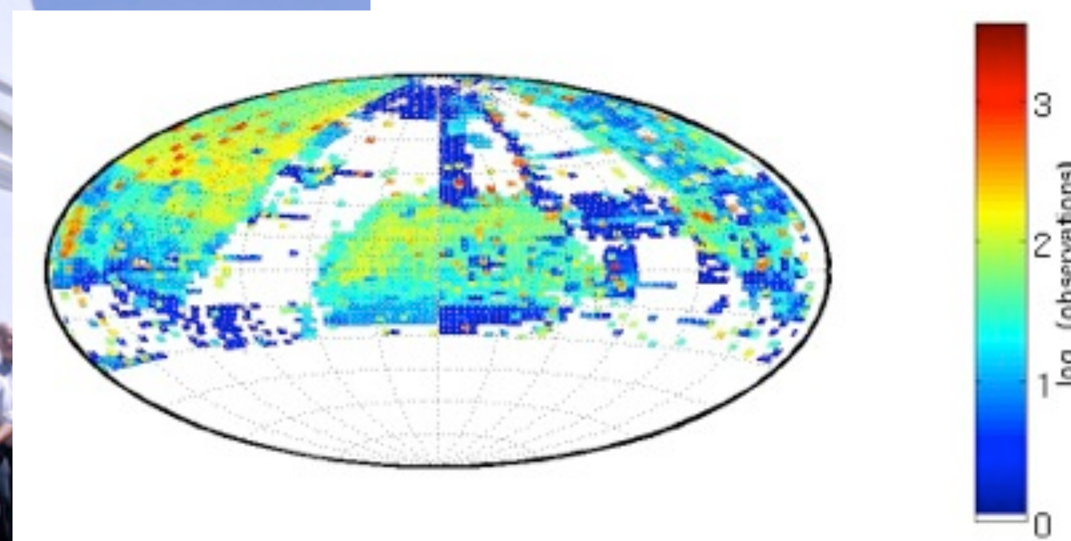




PTF: Palomar Transient Factory

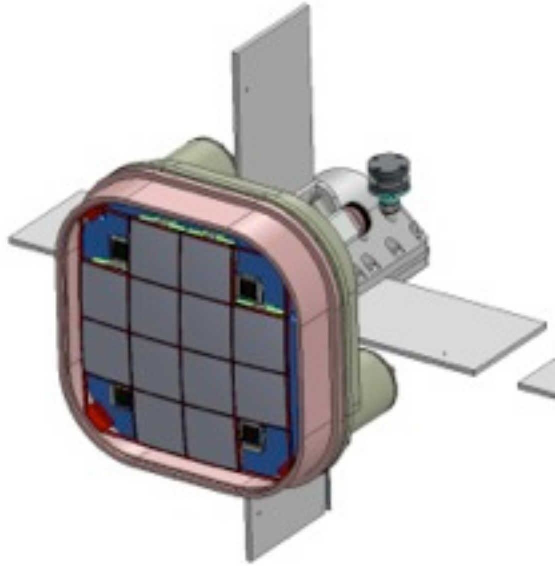
Palomar 48-in, 7.2 deg^2 camera
Currently BigBOSS depth over 5000 deg^2 R-band, 1500 deg^2 g-band
Tied to SDSS photometric system





ZTF: Zwicky Transient Factory

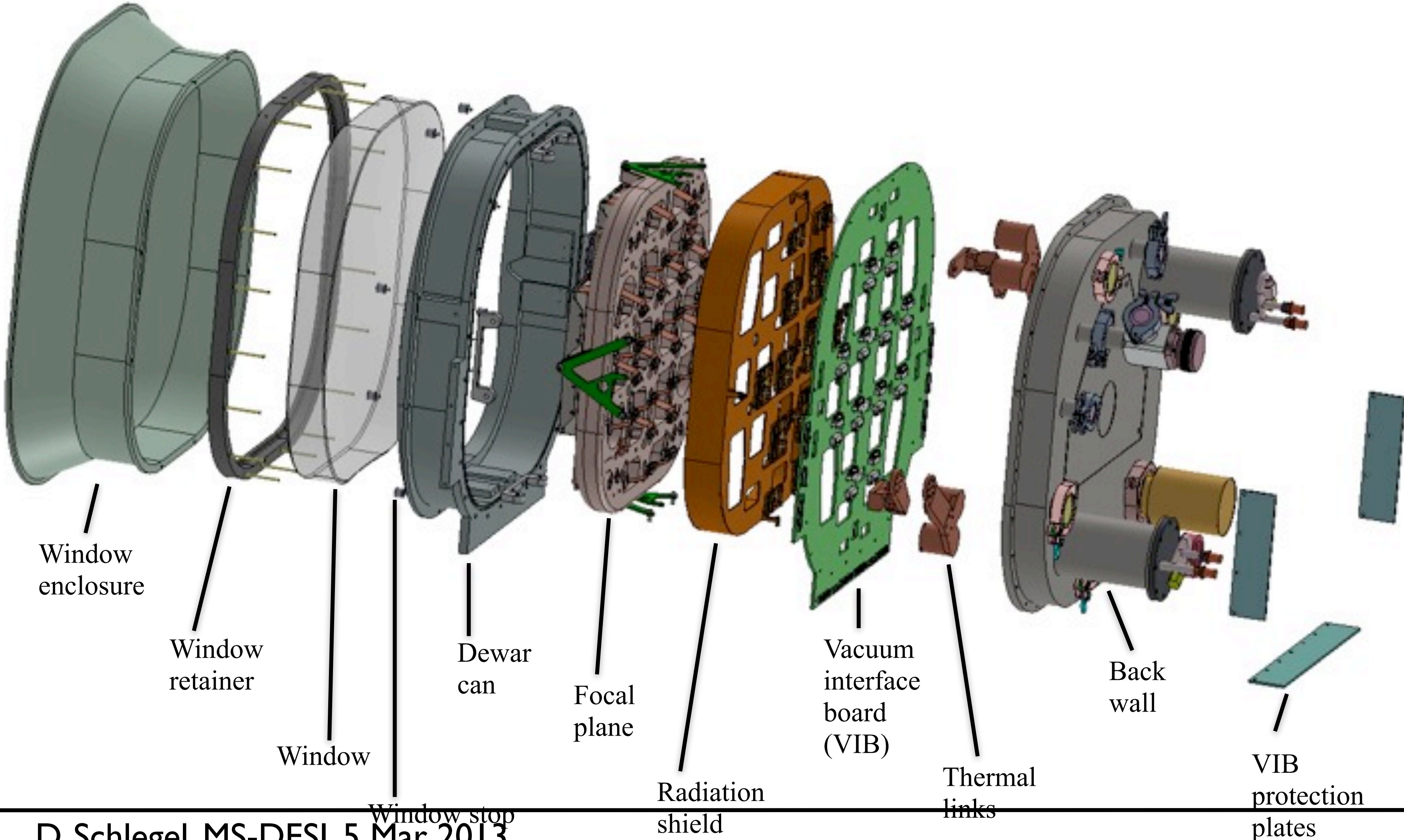
Upgrades PTF on Palomar 48-in, 7 deg^2 -> 36 deg^2 camera
Survey BigBOSS footprint in 2015-2018



Telescope	AΩ
*i*PTF / PTF	8.7
DES	11.7
ZTF	46.6
LSST	82.2

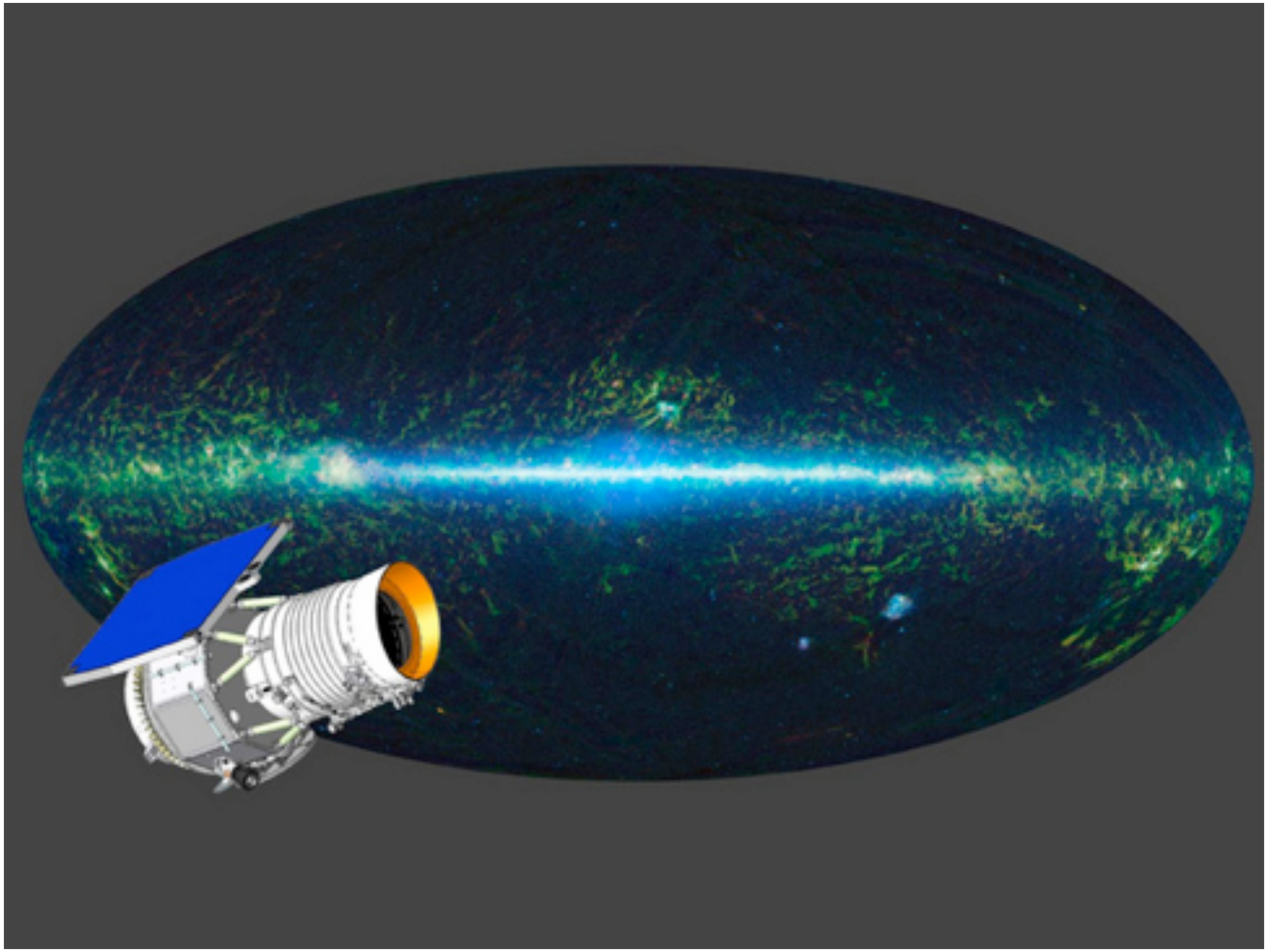
ZTF: Zwicky Transient Factory

Upgrades PTF on Palomar 48-in, 7 deg^2 -> 36 deg^2 camera
Survey BigBOSS footprint in 2015-2018



WISE satellite

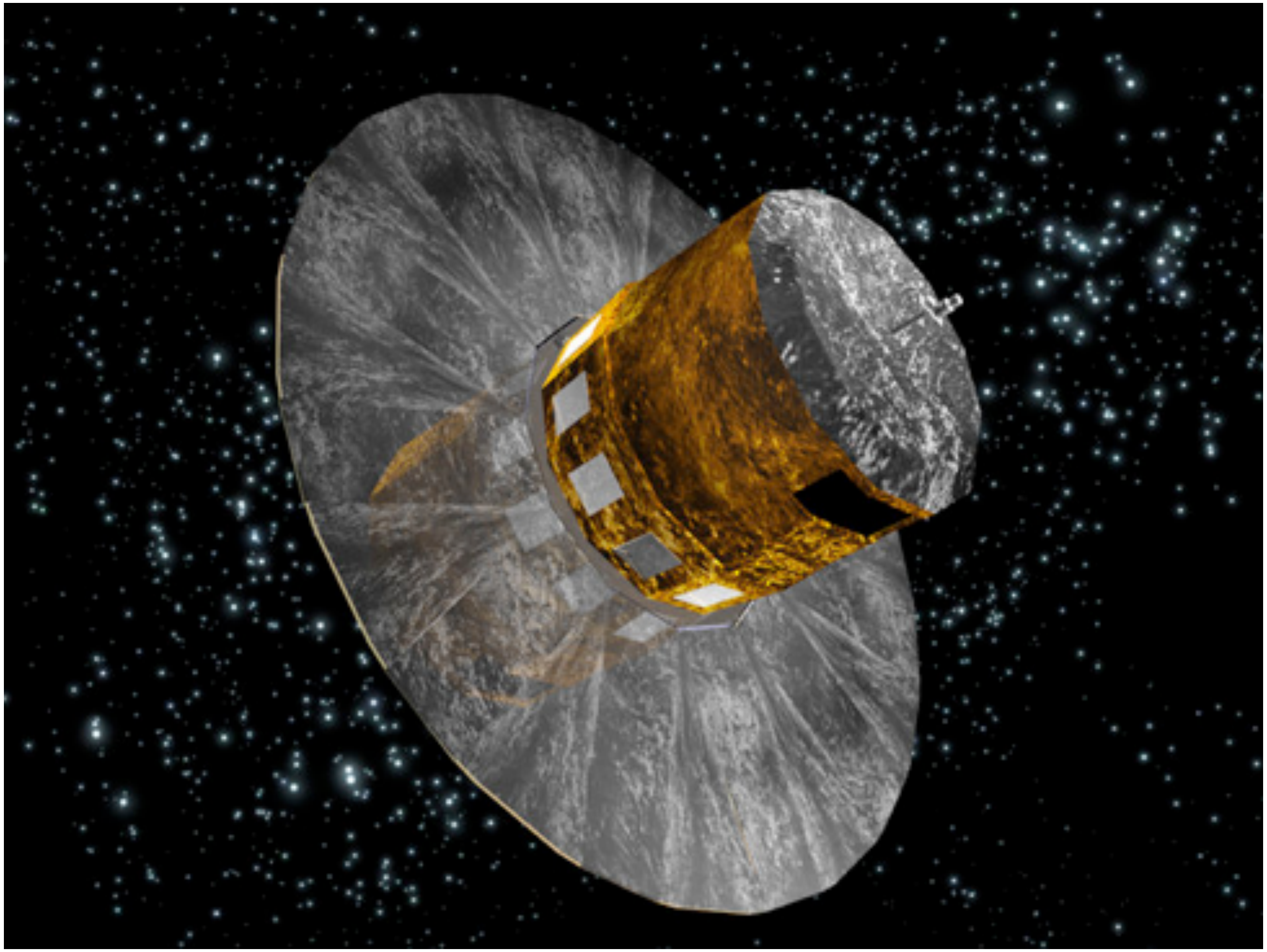
Infrared photometry in 3.4, 4.6, 12, 22 micron
Full sky / completed 2012



GAIA satellite

Full-sky astrometric solution >100X better than USNO+SDSS
- **0.01 milli-arcsec at G=15, 0.3 milli-arcsec at G=20**

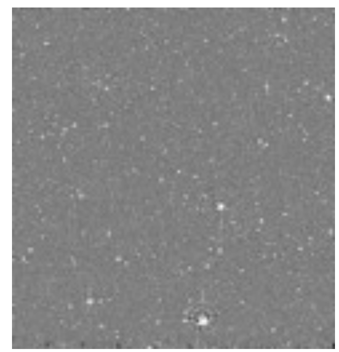
Launch 2013, 1st release catalog 2015



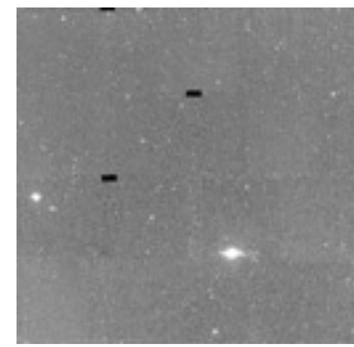
Targeting tests in CFHT W4 field

- Assembled a panchromatic photometric dataset centered on the CFHT-w4 field (22:13:18 +01:19:00 J2000)
- Goal is two-fold:
  - Test BigBOSS target selection from datasets of varying quality
  - Developing code for uniform photometry measurements using forward modeling techniques (aka 'Tractor' – led by Dusting Lang)
- Datasets include:
  - SDSS S82 *ugriz*
  - SCUSS *u*-band
  - CFHT *ugriz* + CS82 shapes
  - PS1-SAS2 *grizy*
  - PTF gR
  - MOSAIC R
  - *WISE* W1-W4
- Initial "staging" requires raw frames have an astrometric solution and measured PSF
- Data is located in the BigBOSS project directory on NERSC

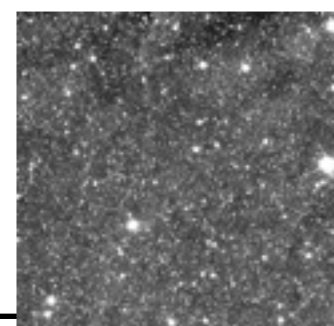
CFHT



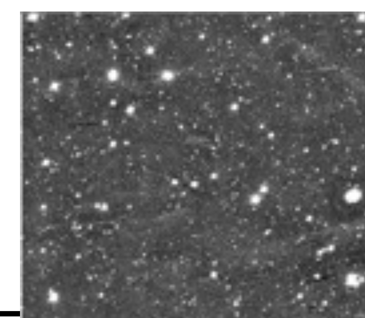
SCUSS



WISE



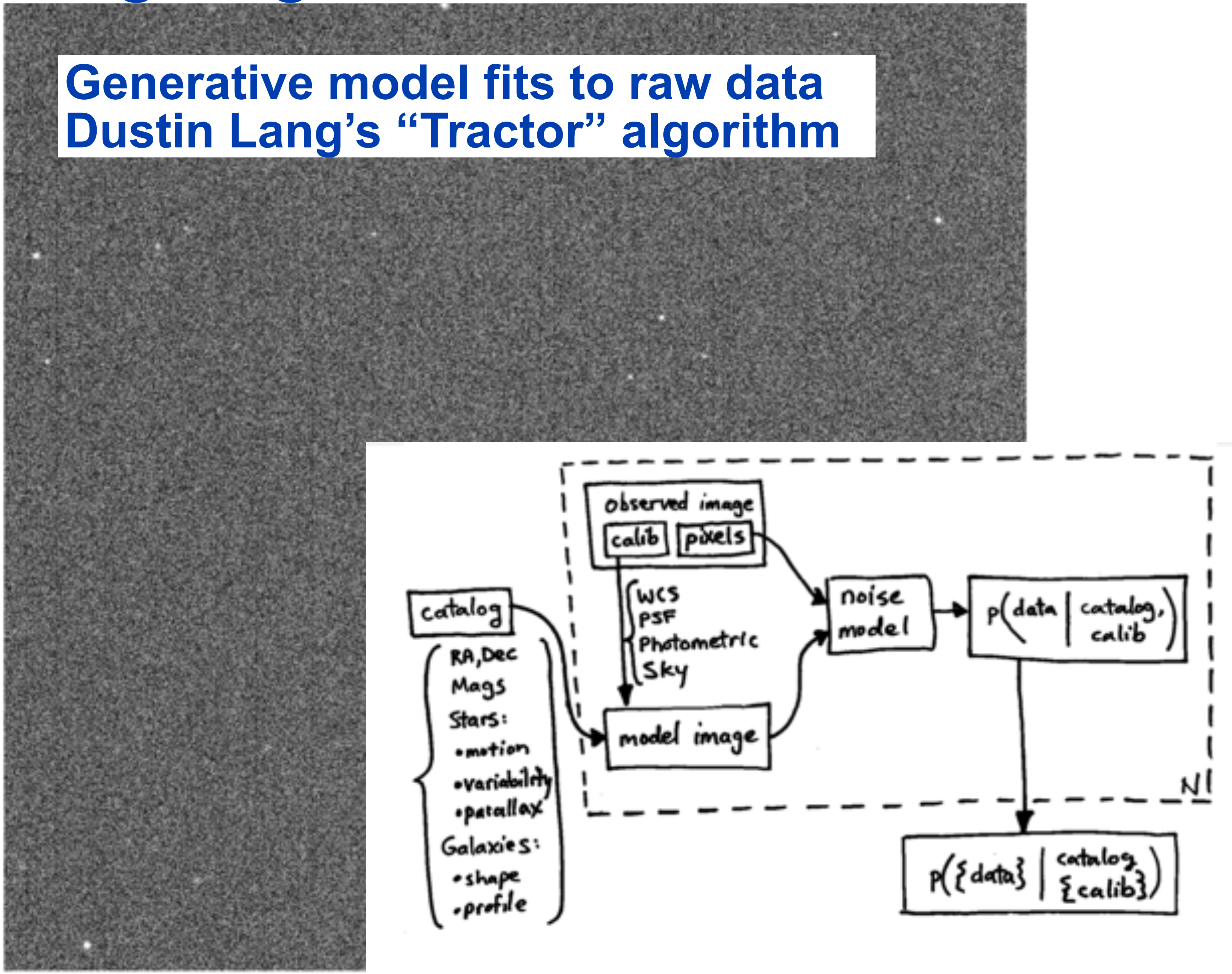
PS1-SAS2



* Not all to same scale

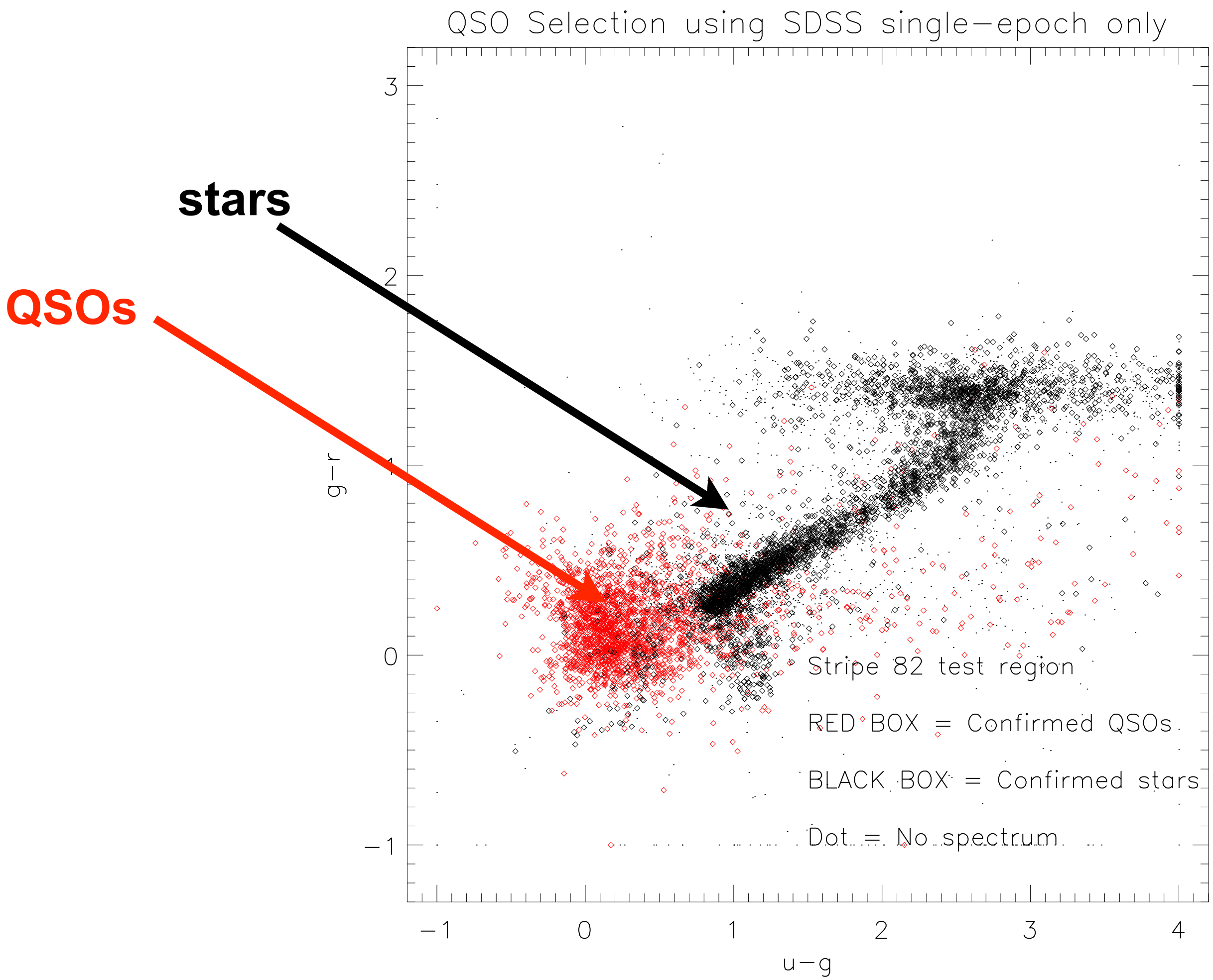
Targeting tests in CFHT W4 field

Generative model fits to raw data
Dustin Lang's "Tractor" algorithm



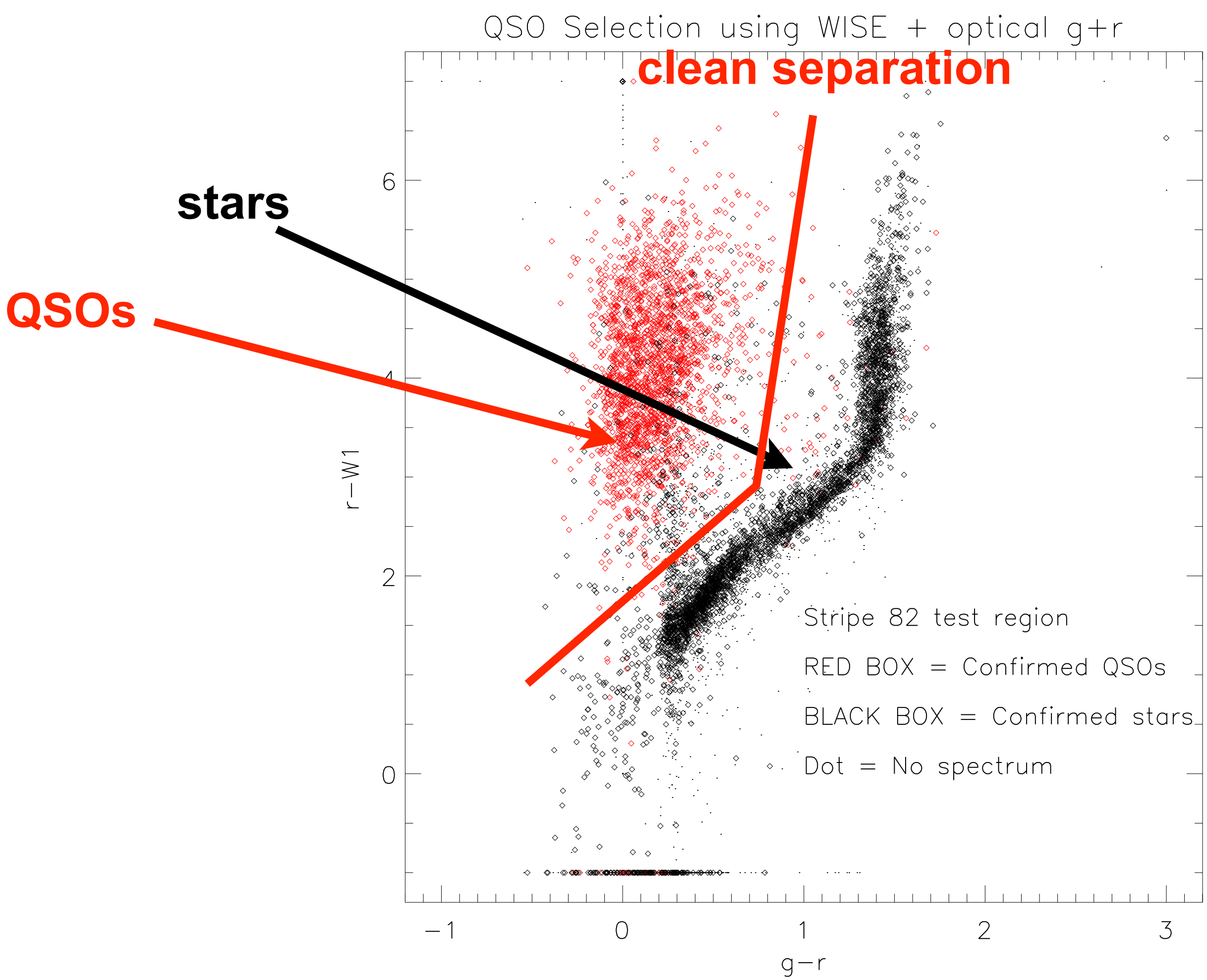
Targeting tests: SDSS + WISE

QSO selection in BOSS from optical colors
suffers ~50% completeness, and ~50% contamination from stars



Targeting tests: SDSS + WISE

QSO selection using "Tractor"-like photometry of WISE infrared images
Problem solved!



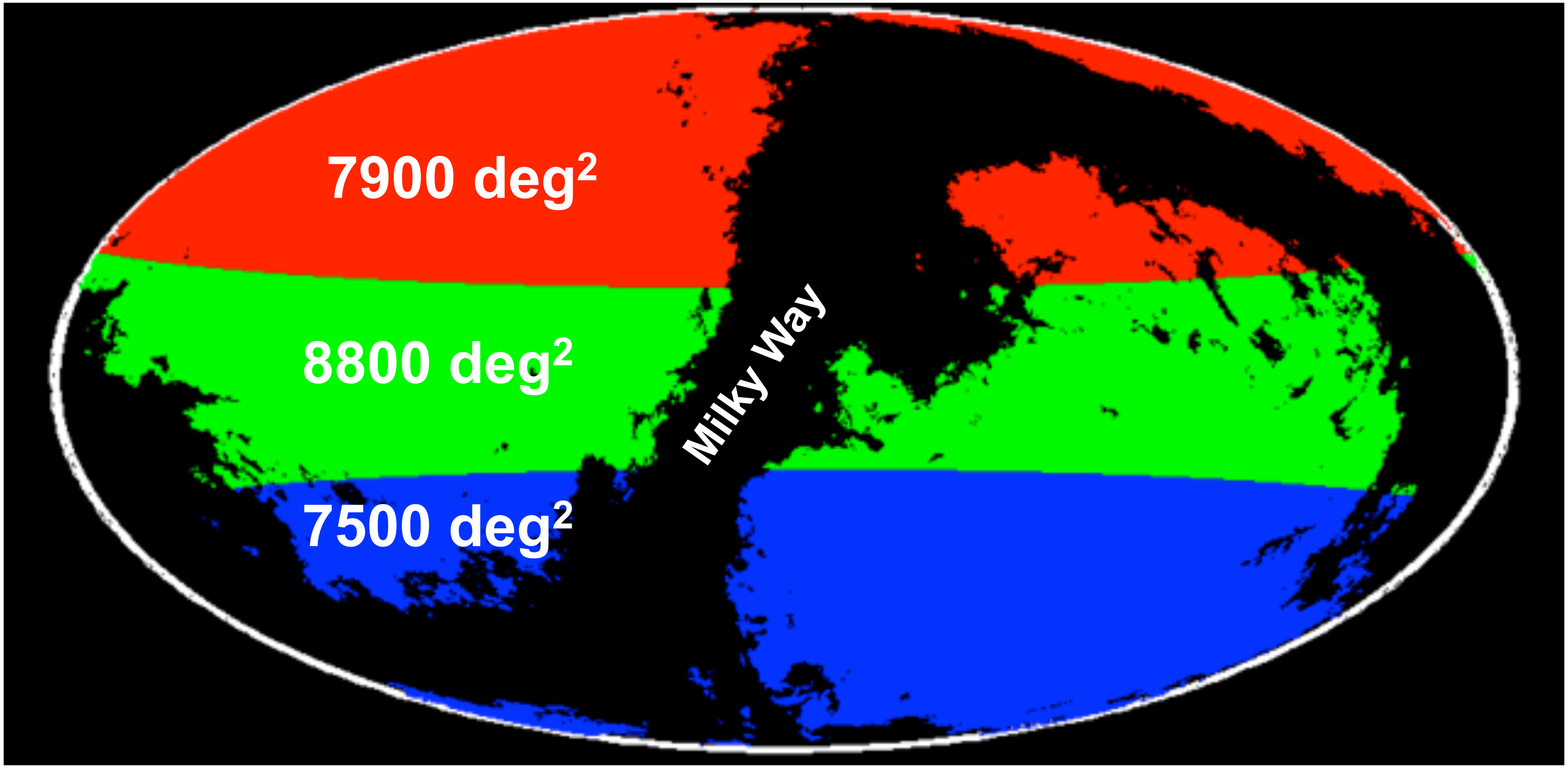
Other imaging resources in North

Other telescope could augment targeting in North + equatorial zones:

Pan-STARRS, CFHT, KPNO/MOSAIC, WIYN pODI, Subaru HSC

In South + equatorial zones:

CTIO/DECam

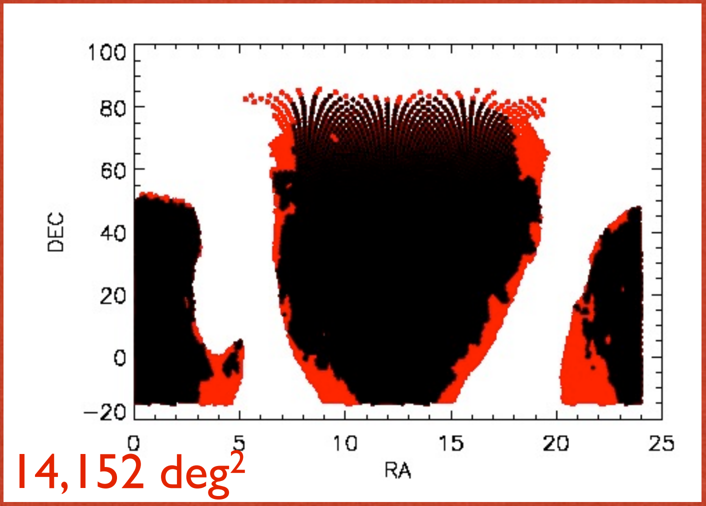


BigBOSS survey strategy

Observability windows; dynamic exposure times to uniform spectro S/N

BIGBOSS FOOTPRINT

- Observing simulations: maximize "S/N" threshold used to get a 14,000 deg^2 region inside this footprint.
- Work south to north (hard to easy), in a 5-year plan.
- Results when using first year for full footprint QSO pass are similar.
- Iterative procedure. Variables: extinction, exposure time, airmass.
- Further hand-trimming of footprint required.

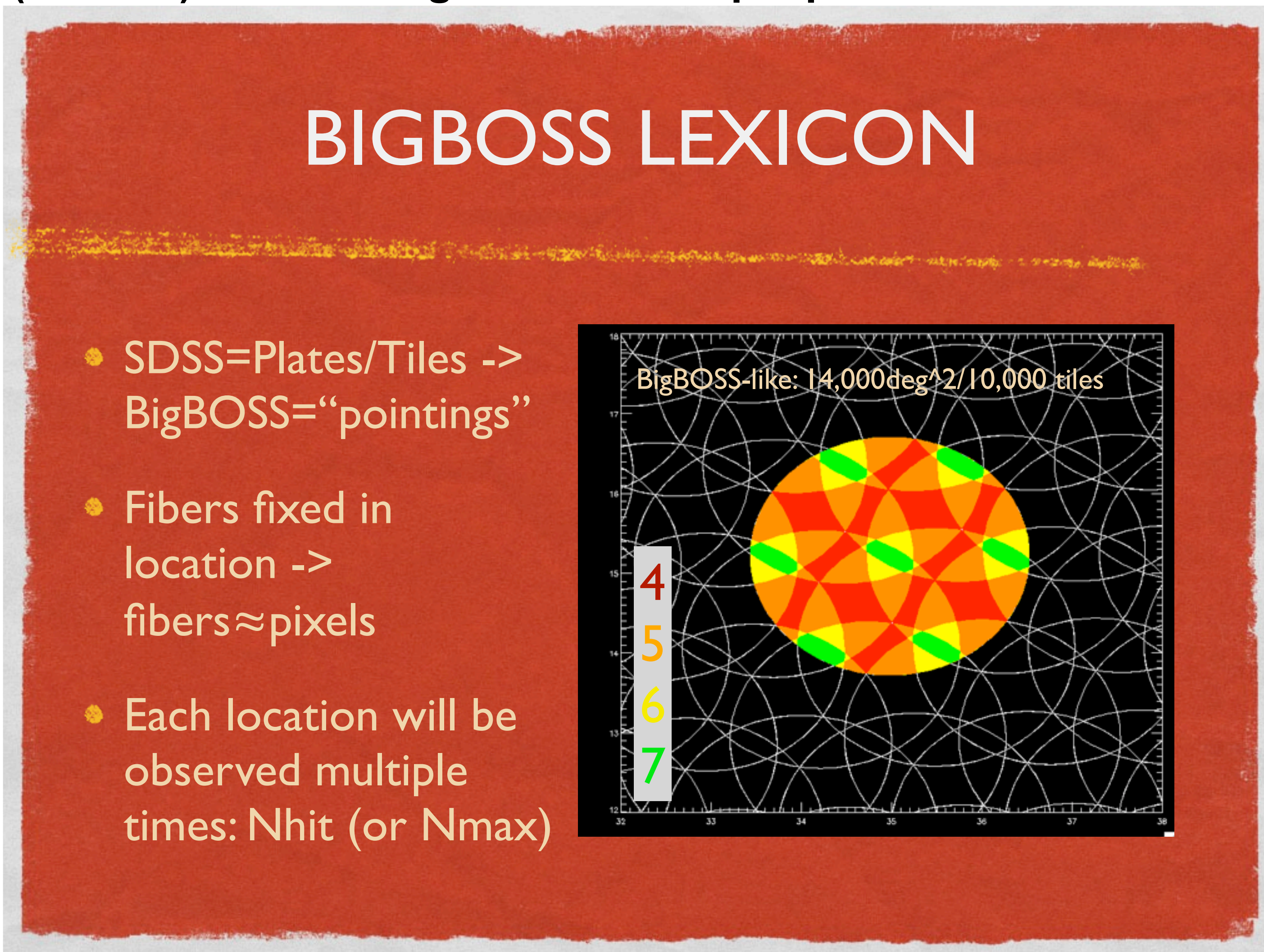


Wednesday, October 10, 12

Kyle Dawson

BigBOSS survey strategy

Circular (not hex) tiles for large area + multiple passes



Wednesday, October 10, 12

Jeremy Tinker

BigBOSS survey strategy

Fiber assignments for recovery of BAO+RSD
Optimizing # of targets does worse!

CLUSTERING RESULTS

- Order of priority matters. ELGs dominate, so maximize LRG/QSO completeness by ranking them higher.

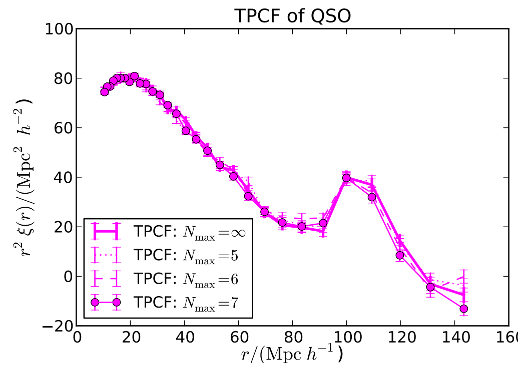


Figure 16. TPCF of QSOs with "Q-L-E-Q-L rotational" sequence of priority. $N_{\max} = 6$ would be good enough.

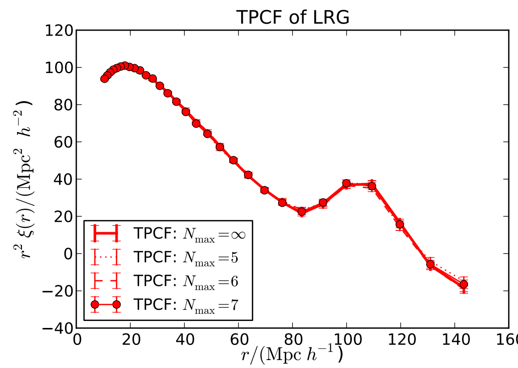


Figure 17. TPCF of LRGs with "Q-L-E-Q-L rotational" sequence of priority. Results with different $N_{\max}$ almost overlap.

Wednesday, October 10, 12

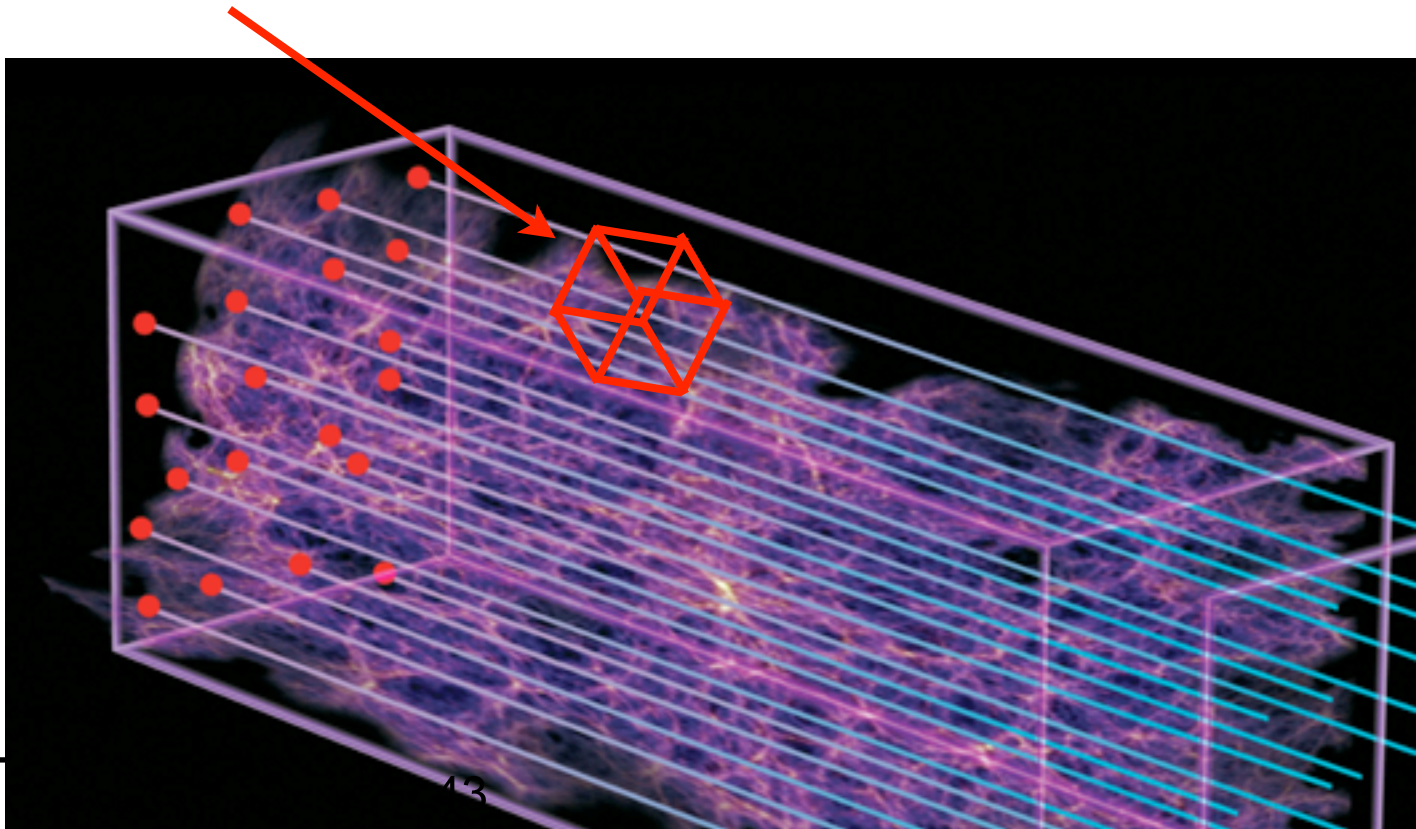
Lile Wang, Martin White

BigBOSS survey strategy

Interpreting BAO+RSD survey relies upon a “complete sample”,
i.e. selection function for each box in (RA, Dec, z) very well-understood

Example: BOSS is 98% complete; the additional 2% well-understood

“Fancy” target selection, tiling strategy, etc., would spoil this
(Ask Martin for the technical definition of “fancy”)

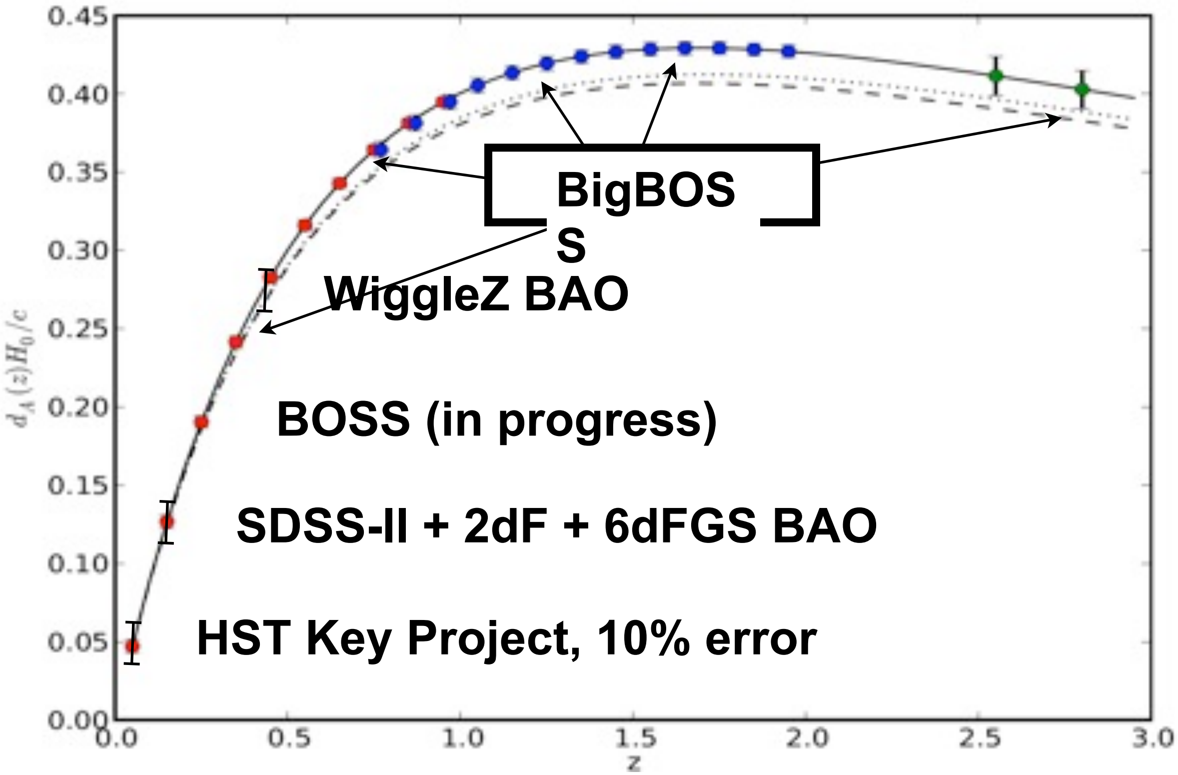


BigBOSS science reach: BAO

Dark energy from Stage IV BAO

- *Geometric probe with 0.3-1% precision from z=0.5 -> 3*
- *35 measurements with 1% precision*

BigBOSS BAO “Hubble diagram”

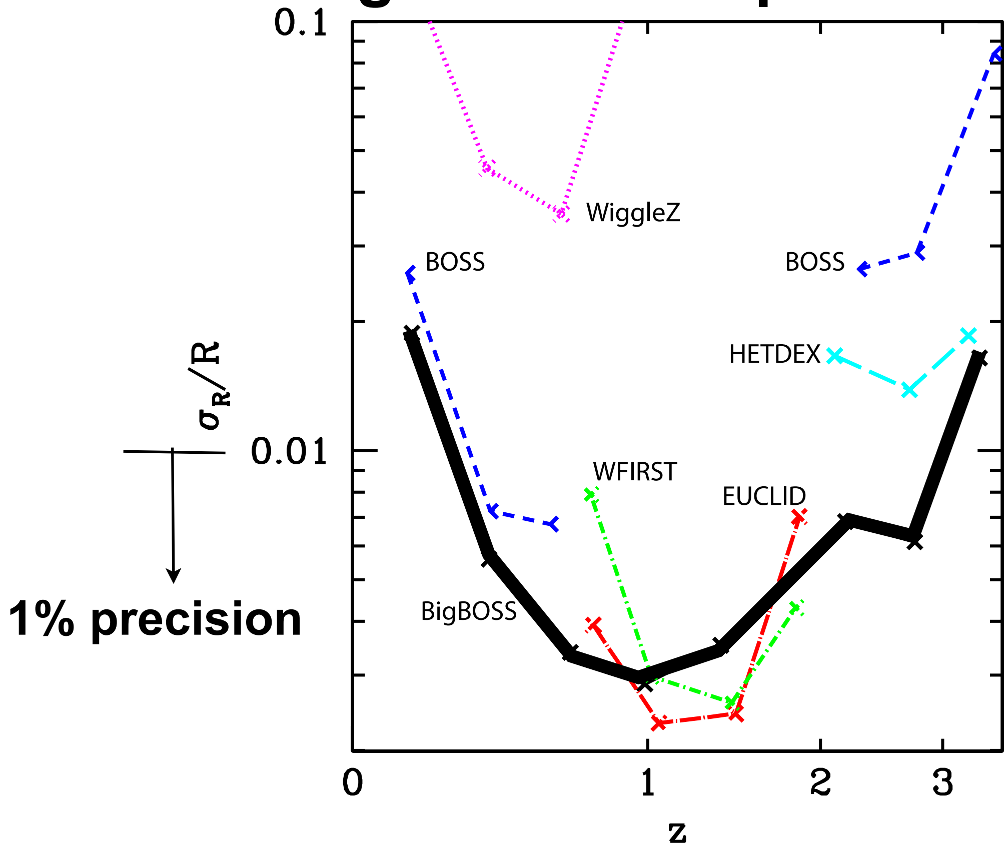


BigBOSS science reach: BAO

Dark energy from Stage IV BAO

- *Geometric probe with 0.3-1% precision from z=0.5 -> 3*
- *35 measurements with 1% precision*

BigBOSS BAO precision

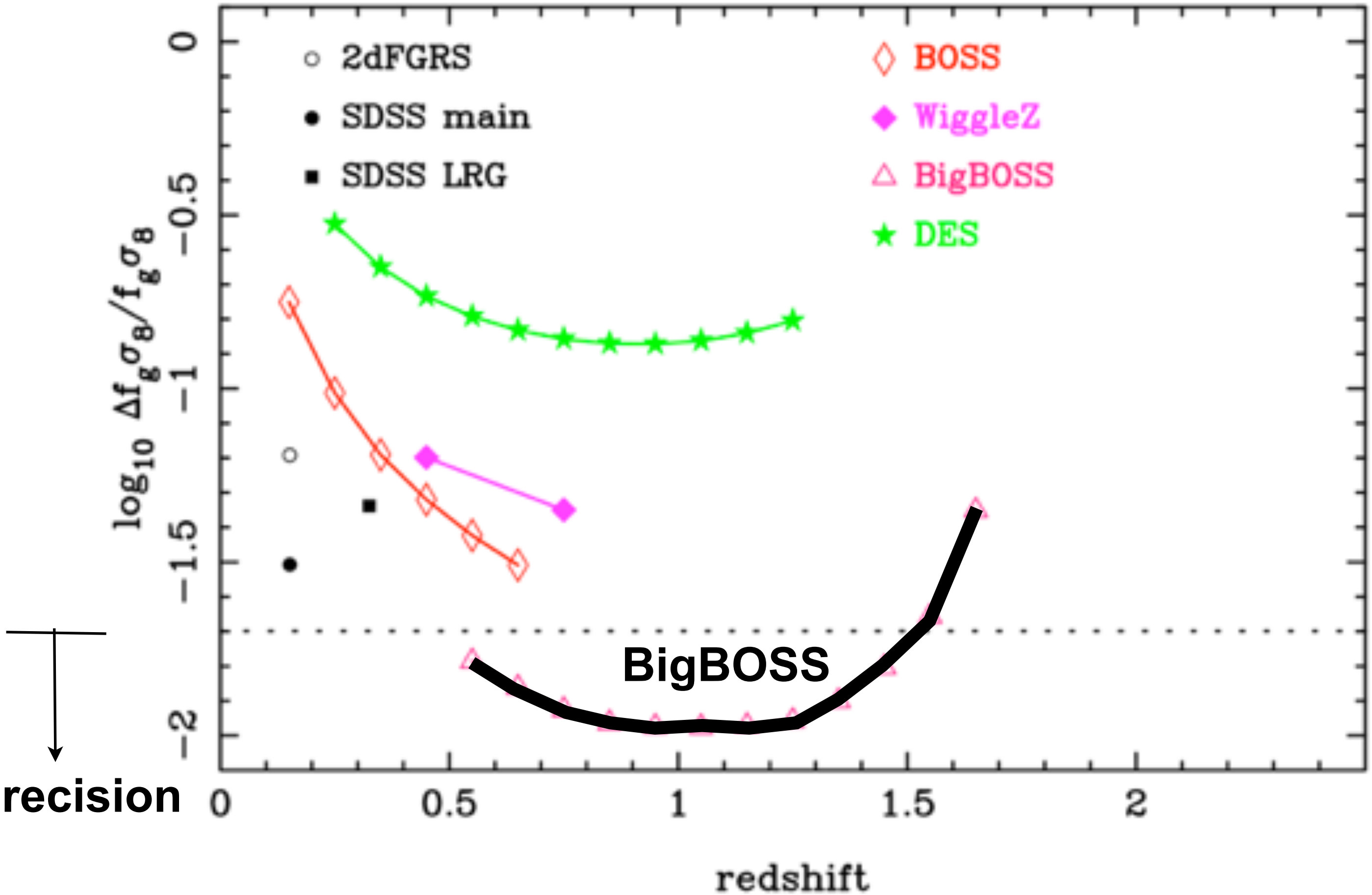


BigBOSS Stage IV science reach

Dark energy from Stage IV RSD

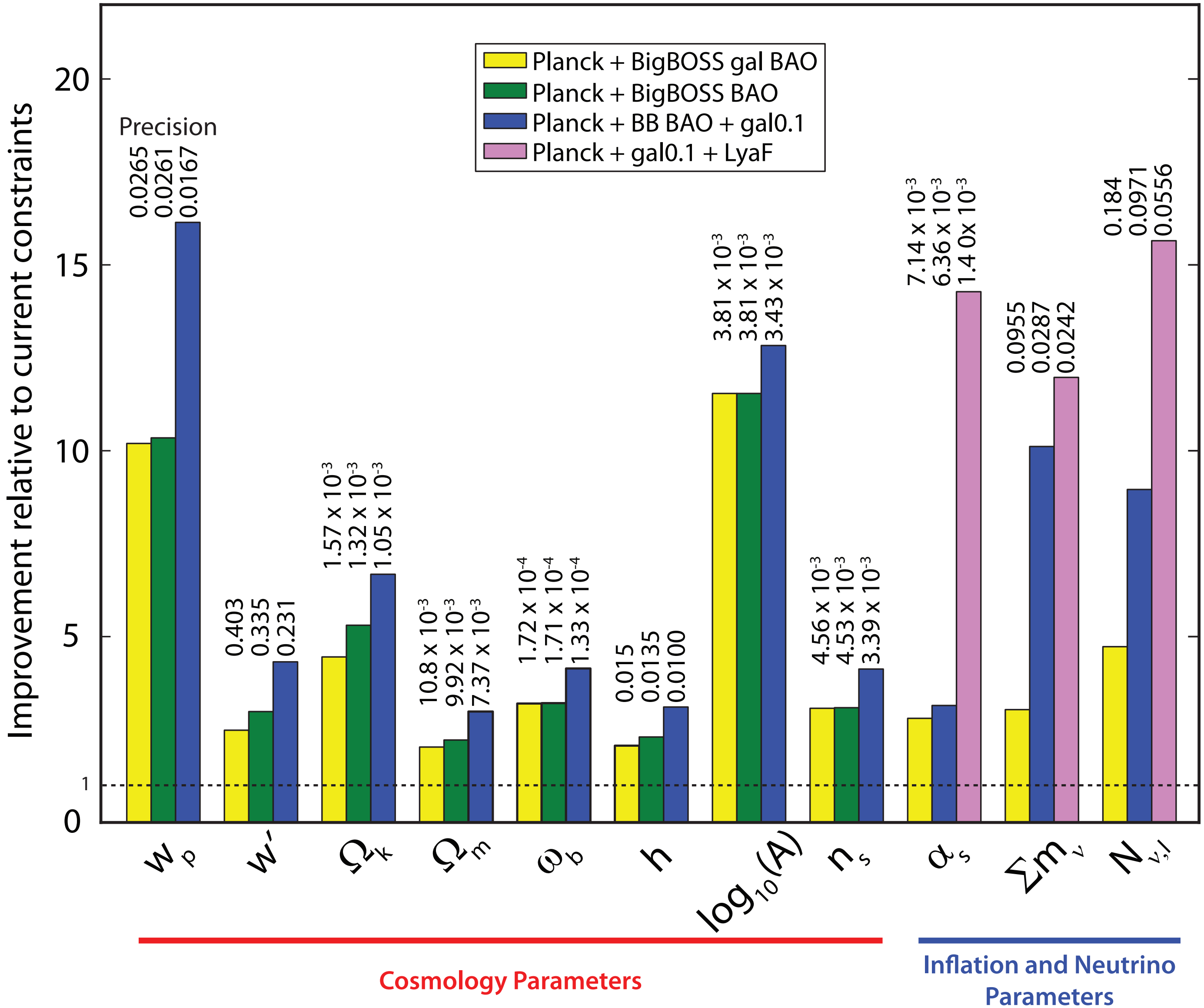
— *Gravitational growth with 2% precision from z=0.5 -> 1.5*

BigBOSS RSD precision



2% precision

BigBOSS Stage IV science reach



BigBOSS optimization

Figure-of-Merit improvement for throughput above baseline design
Near design optimum in cost per throughput

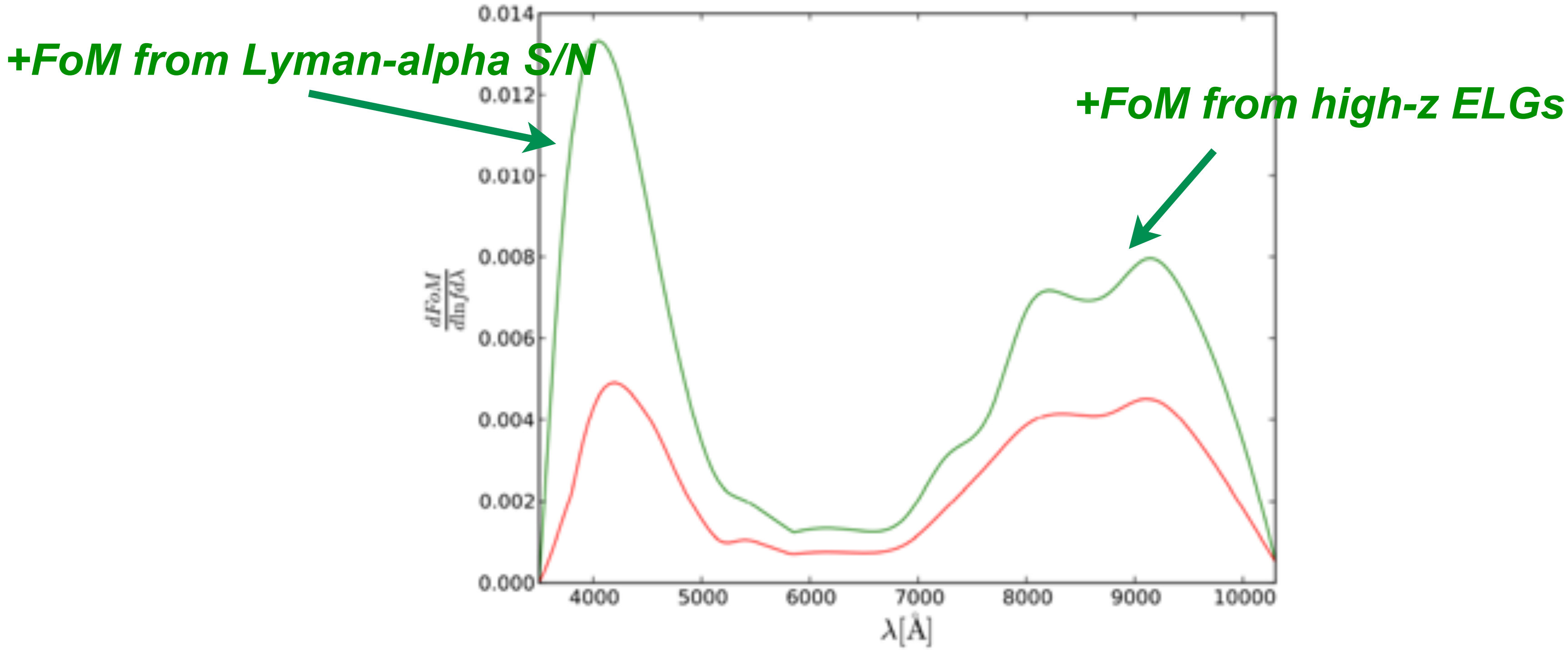


FIG. 2. $\frac{dFoM}{d\ln f d\lambda}$ where $d\lambda$ here is intended to mean that you could integrate it over λ. This is using BAO only, combining ELGs and Lyα forest. LRG and quasar numbers are fixed. Green is signal change, red is negative sky change. Planck and a 5% H_0 prior are the only additional data. All of this only makes sense as a perturbation around the baseline.

Pat McDonald

BigBOSS instrument + survey requirements flowdown

BigBOSS Scientific Objective: Perform a Stage IV BAO Spectroscopic Survey

LEVEL 1

Scientific Requirements

- Measure the distance scale error σ_R/R to $< 1\%$ for $0.5 < z < 3.0$
  (in 6 bins with $\Delta\ln(1+z) = 0.2$)
- Measure H(z) to 1% up to z=2.5
  (in 4 bins at $<z> = 0.7, 1.1, 1.5, 2.5$)
- Constrain growth, $\sigma_8(z)$ f(z), with <2% relative error
  ($\Delta z = 0.1$ bins, $k_{max} = 0.2$, for $0.5 < z < 1.5$)
- Measure galaxy power spectrum to < 1% up to z=1.5
  ($\Delta k = 0.02$ Mpc/h bins, $k_{max} = 0.3$)

Additional Scientific Goals

- Inflation: constrain spectral index and its running to < 1%
- Measure the sum of neutrino masses $\Sigma\, m_\nu$ with $\sigma < 0.020$ eV

LEVEL 2

Data Set Requirements

- Survey Area: 14,000 sq deg
- Redshift range:
  - LRGs $0.5 < z < 1.0$
  - ELGs $0.5 < z < 1.6$
  - Tracer QSOs $0.5 < z < 3.5$
  - Ly-α QSOs $2.2 < z < 3.5$
- Galaxy *dN/dV* > 1×10^{-4} $(h/Mpc)^3$
- Number of redshifts: 20M
- Redshift accuracy:
  - $\sigma_z < 0.001(1+z)$ rms
  - < 5% catastrophic failures
  - resolve OII doublet for $0.76 < z < 1.6$

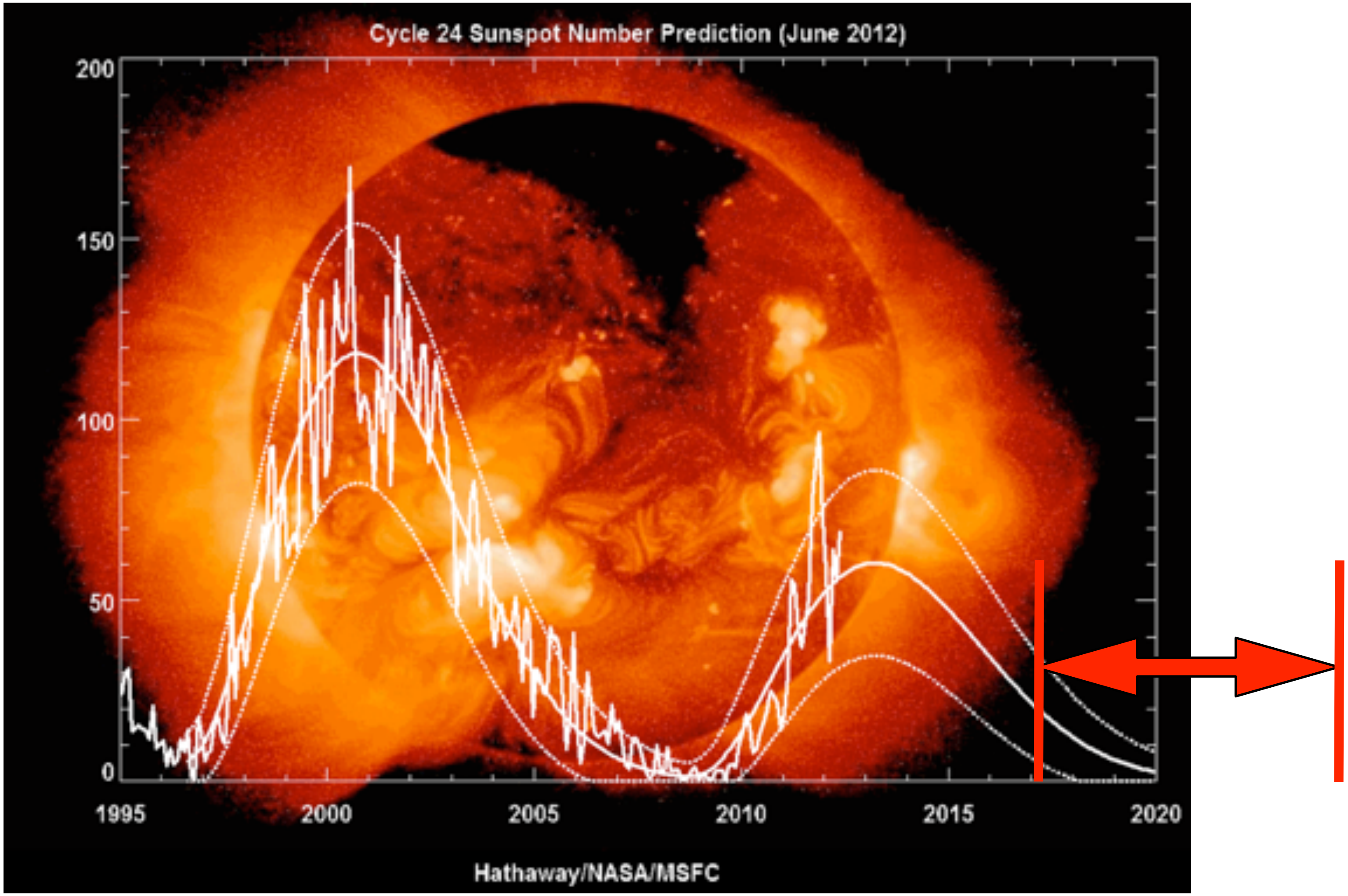
LEVEL 3

Instrument Requirements

- Operational Constraints
  - < 500 nights
  - Instrument compatible with Mayall telescope
  - Preserve use of f/8 secondary
  - Typical seeing, weather for site used in forecasts
- Field of View: 3 deg diameter
- Number of Fibers: 5000
- Operational overheads: total < 60 s/exposure
- Spectral Range and Resolution
  - 360 nm < λ < 555 nm: R > 1500
  - 555 nm < λ < 656nm: R > 3000
  - 656 nm < λ < 980 nm: R > 4000
- Optical Throughput vs λ
- Fiber Positioning Error < 0.35 asec (rms, includes actuators, guiding, tracking, target astrometry)

Excellent planning for MS DESI time window 2017-2022

MS DESI achieves higher S/N with low solar activity / darker night sky
"Weather forecast" for the Sun: 2017-2022 will be low solar activity



MS-DESI Timeline to results

First experiment that can deliver stage IV results by 2020

SDSS delivered BAO results 6 years from start
(w/ 3 yrs data in 2005)

BOSS delivering BAO results 2.5 years from start
(w/ 1.5 yrs data)

Sep 2009 Commissioning
Dec 2009 Survey start
Jul 2011 Data set defined
Feb 2012 BAO results

MS-DESI to deliver BAO results 2 years from start
(w/ 1 yr data)

Dec 2017 Commissioning / pilot observations
Sep 2018 Survey start
Sep 2019 Data set defined
Jan 2020 BAO results